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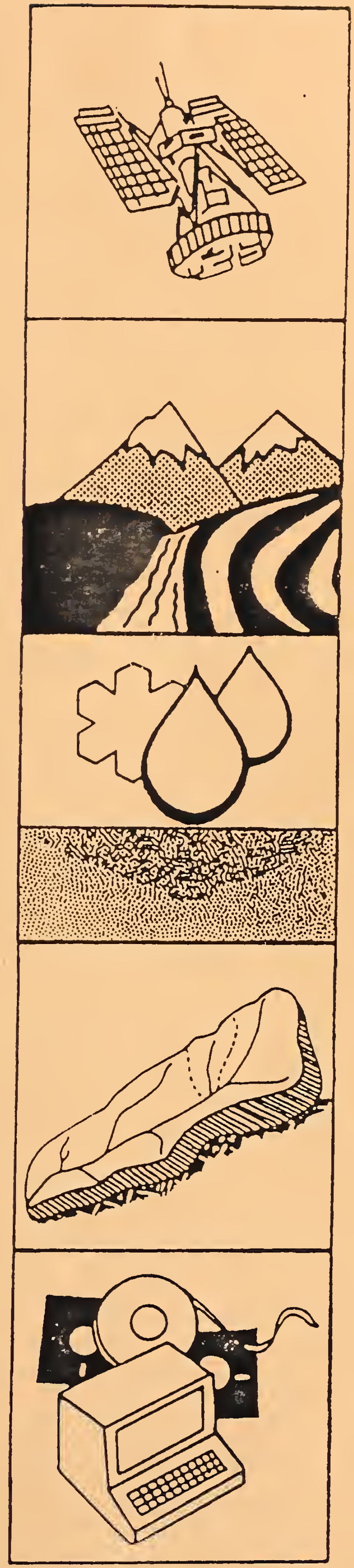

RUNOFF CURVE NUMBERS FOR RANGELAND FROM LANDSAT DATA

A. W. ZEVENBERGEN

January 1985

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January 1985

Table of contents

Abstract

1. Background 1

2. Introduction 3

2.1 Outline 3

2.2 Runoff curve numbers 4

2.2.1 The SCS model 4

2.2.2 The statistical approach 10

2.3 Landsat images 14

3. Preparation of data 21

3.1 Curve numbers and watersheds 21

3.2 Landsat response 24

3.2.1 Sources 24

3.2.2 Mapping and data retrieval procedures 26

3.2.3 Correcting and calibrating procedures 28

3.2.4 Reflectance index models 31

3.2.5 Reflectance index models and ground truth 36

4. Results 38

4.1 Relationships between curve numbers and reflectance index models 38

4.2 Significance of seasonal fluctuation of Landsat data 41

5. Conclusions and recommendations 43

References 45

List of abbreviations and symbols 48

Appendices 49

RUNOFF CURVE NUMBERS FOR RANGELAND FROM LANDSAT DATA

1. Background

Within the framework of a MSc program at the Department of Hydraulics and Catchment Hydrology of the Agricultural University in Wageningen, the author conducted a study at the Hydrology Laboratory in Beltsville, Maryland. The Laboratory is part of the Agricultural Research Service (ARS) of the United States Department of Agriculture. The research program at the Hydrology Laboratory is directed at developing methodology for studying hydrologic problems that encompass large areas of the country and will have a widespread and universal application. The two approaches that are emphasized are hydrologic modeling and remote sensing. Projects are carried out cooperatively with the regional ARS hydrology research centers, state and other federal agencies. This work contributes to the research on the hydrology component of the SPUR model (Simulation of Production and Utilization of Rangelands), a physically based, rangeland simulation model developed by ARS to aid both resource managers and researchers.

SPUR is composed of five basic components: 1) climate; 2) hydrology; 3) plant; 4) animal (both domestic and wildlife); and 5) economic. The model is driven by daily inputs of rainfall, maximum and minimum temperatures, solar radiation, and wind run, either obtained from actual weather records or stochastically generated. Although specifically intended to furnish the SPUR model with an input parameter on which the water balance, erosion, and water quality aspects depend, i.e., the runoff curve number, this project also has significant potential for general use by the Soil Conservation Service (SCS) in the western USA.

The term rangeland or range refers to any kind of grazable land, from desert, its most marginal form, to grazed forests, natural grasslands, and marshes. In the United States there are 331.8 million hectares of rangeland. It is because of this great expanse of rangeland, rather than its productivity relative to forest and croplands, that rapid, low-cost evaluation and management techniques are required.

The runoff curve number (CN) method employed as a rainfall runoff relationship in this study is widely used through the spectrum of hydrologic application by federal, state and private hydrologists. At some point metric units should be used, however, in general the philosophy behind the expression "in Rome, do as the Romans do" is practiced, mainly with the possible applications of this research in mind.

2. Introduction

2.1 Outline

The main objective is to develop a procedure for estimating runoff curve numbers (CN) for rangeland from existing Landsat multispectral scanner (MSS) information. The approach used in this study is to analyse remote sensing data for small watersheds and to compare the results to CN values determined with conventional rainfall (P) and runoff (Q) records.

Earlier research has shown that CN can be estimated using Landsat imagery and the SCS model (Bondelid, et al., 1980, Ragan and Jackson, 1980; Slack and Welch, 1979). The utilization of Landsat data in a model is generally time and cost effective because the Landsat data are in machine readable form. Therefore, digital computers can be used for the required computations. In contrast to prior research which used remote sensing classified land cover and conventional soils maps to determine CN, the intention of this study is to relate Landsat MSS data directly to the measured CN of rangeland watersheds. The reason for omitting soils data from the final model is that soils maps are generally not available for vast areas of the world as well as for large parts of the western USA. Figure 1 shows areas for which SCS soils maps are available as of January 1, 1984.

A number of rangeland watershed records have been collected and analysed to develop basic P-Q relations and to get some insight into the range of CN values and the hydrological behavior of the various rangelands. Ten of these watersheds were chosen for this study to provide a sample of data that was representative of the many cover-climatic complexes found in rangelands. For

the selected watersheds Landsat computer-compatible tapes were obtained and the spectral response was correlated with their CNs.

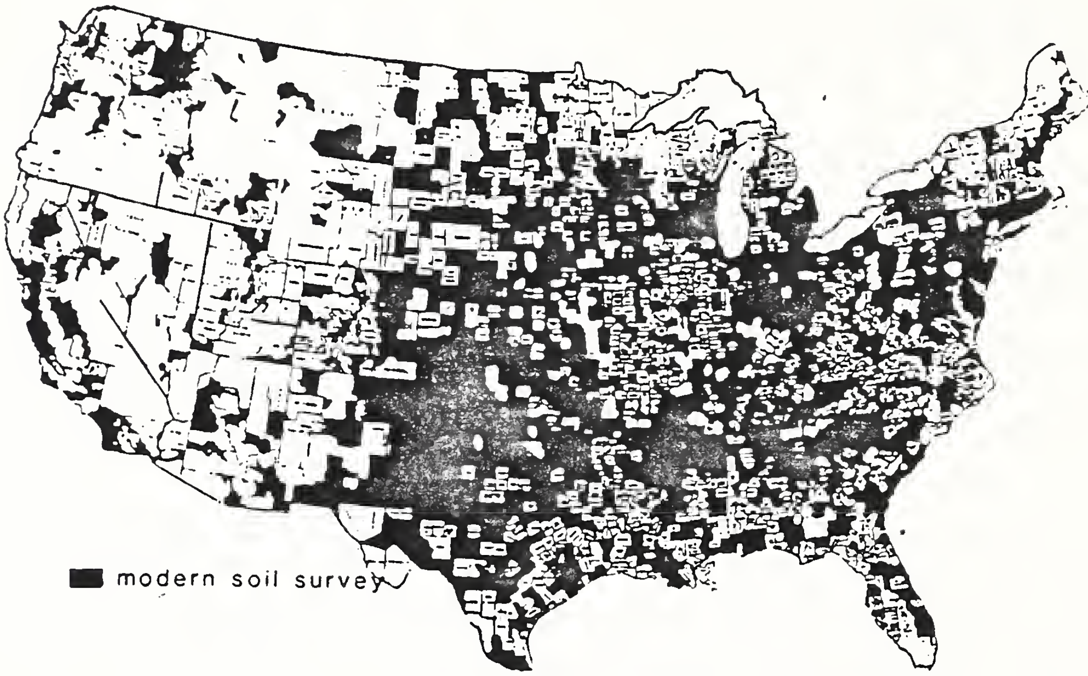

Figure 1. Availability of modern soil surveys as of January 1, 1984.

Figure 2 presents a flow diagram of the procedures followed in this research. In the concluding chapter an outline and recommendations are given for the additional research needed to develop a complete methodology

2.2 Runoff curve numbers

2.2.1 The SCS model

In the early 1950s the Soil Conservation Service (SCS) of the USDA developed a procedure for estimating stormflow volumes from rainfall events on small watersheds. The SCS method was designed to use total daily (24 hour) rainfall. The relationships between storm rainfall, watershed characteristics and stormflow are derived in the so called NEH-4, i.e. The National Engineering Handbook, Section 4 (USDA-SCS, 1972).

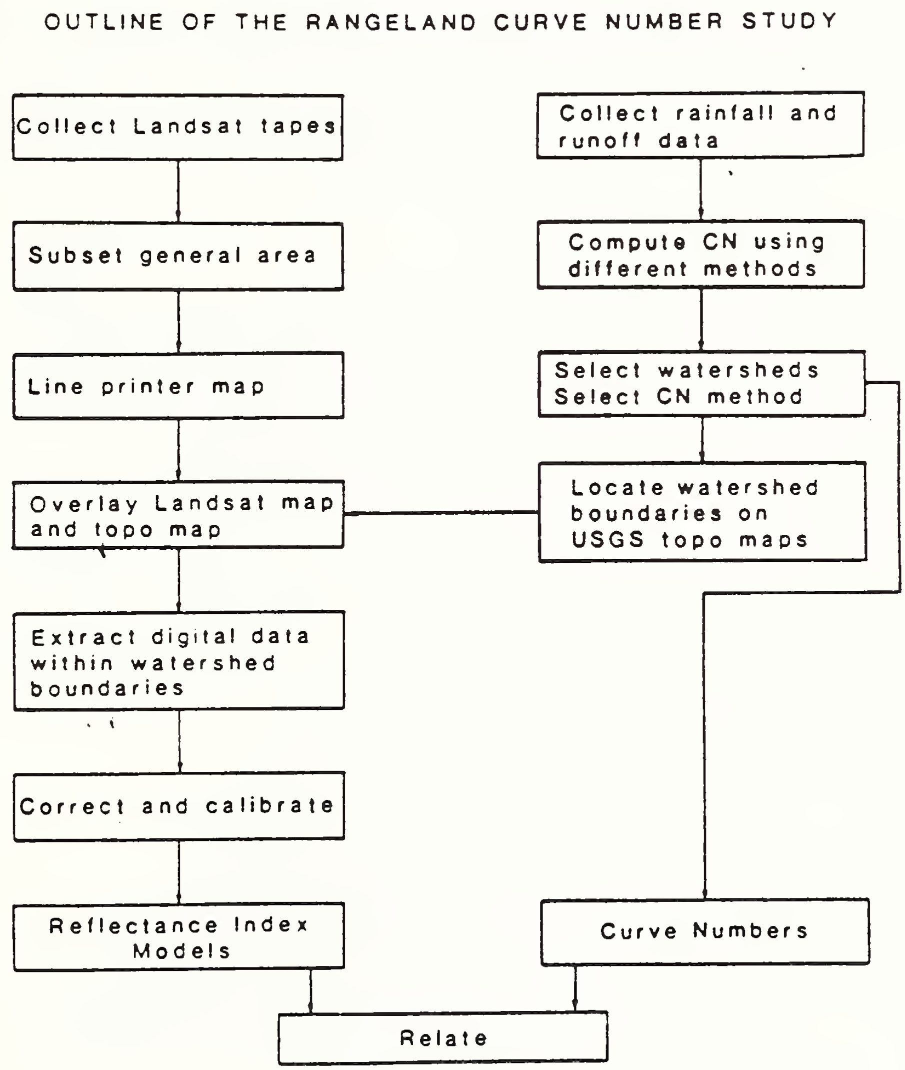

Figure 2. Flow diagram of the rangeland curve number study.

Analyses of rainfall and runoff records indicates that the rainfall magnitude must be sufficient to satisfy interception, depression storage, and the infiltration quantity before the start of runoff. This threshold is called the initial abstraction, Ia.

After start of runoff, additional loss occurs mainly in the form of infiltration. The total actual retention after runoff begins is given the symbol F, which increases up to some maximum retention, S. The ratio of actual retention F to maximum retention S is assumed to be equal to the ratio of runoff to rainfall minus initial abstraction, which can be expressed as

$$Q/(P-Ia) = F/S \qquad [1]$$

For the limit, as $P \to \infty$, $F \to S$ and the ratio $F/S \to 1$. The ratio of $Q/(P-Ia)$ also approaches 1, although it can never actually reach 1, but for all practical purposes the two ratios approach 1 as $P \to \infty$. When $P = Ia$, $F = 0$ and the ratio of $F/S = 0$. As P becomes greater than Ia the ratio of F/S is still near zero and the $Q/(P-Ia)$ ratio is also near zero. Since the relationship holds at the two end points, it is assumed to hold for all intermediate points. After runoff begins, all rainfall becomes runoff or actual retention. That is.

$$(P-Ia) = F + Q \qquad [2]$$

Solving equations [1] and [2] for Q when $P > Ia$ yields

$$Q = (P-Ia)^2 /((P-Ia) + S) \qquad [3]$$

and when $P \leq Ia$,

$$Q = 0$$

In order to avoid estimatimg both Ia and S, the SCS expressed Ia in terms of S by the empirical relationship

$$Ia = 0.2S \qquad [4]$$

thus simplifying equation [3] to

$$Q = (P-0.2S)^2 \;/\; (P+0.8S)\ , \quad P>0.2S \qquad [5]$$

$$Q = 0 \qquad P \leq 0.2S$$

Since S can theoretically range from zero to infinity, it was transformed to a scale from 0 to 100. The transformation takes the form

$$CN = 1000\ /(S+10) \qquad [6]$$

where

CN = runoff curve number or the hydrologic soil-cover-complex number.

Curve numbers are reflective of land condition, and tables and charts of CN defined on soil type, land use, cover, and watershed moisture status are given in numerous SCS and other agency documents.

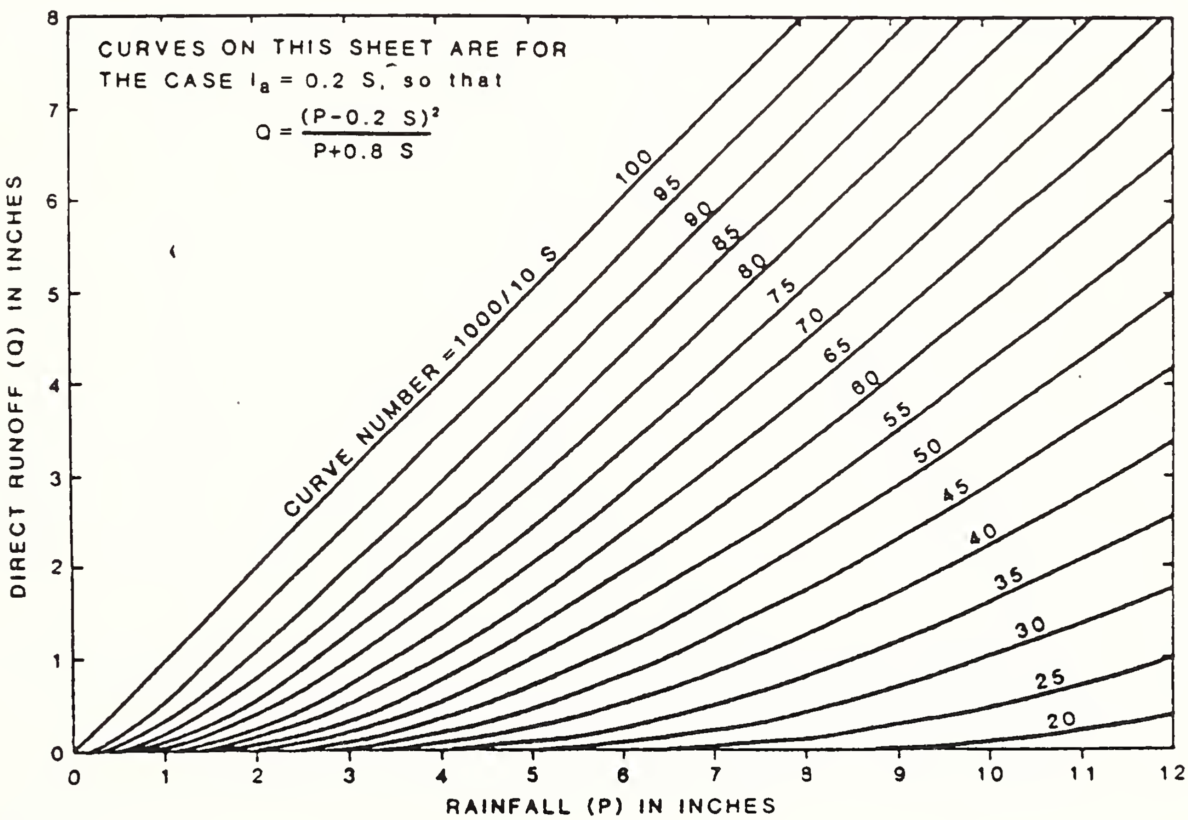

Figure 3. The curve number nomogram.

The watershed moisture status is one of the most influential factors in CN. NEH-4 gives in its Table 10.1 conversions through three antecedent moisture classes, AMC I, AMC II and AMC III, where condition II is the benchmark situation upon which a watershed is described, and conditions I and III are the "dry" and "wet" situations respectively. An abbreviated form of these relationships is given here as Table 1. NEH-4 also gives suggested approximate five-day antecedent rainfall depths necessary to achieve these three categories.

Table 1. Relationships between CN and AMC

Antecedent Moisture Class		
I	II	III
100	100	100
78	90	96
63	80	91
51	70	85
40	60	78
31	50	70
22	40	60
15	30	50

Graphically the direct runoff is estimated from Figure 3 (NEH-4 Figure 10.1). Entering with the total rainfall and CN, the runoff amount is read. For example, a rainfall total of 3 inches and a CN of 80 gives a direct runoff (Q) of 2 inches.

Table 2 is an excerpt of Table 9.1 from the NEH-4. Only the portion for pasture or range, meadow, and woods are presented.

Table 2. Runoff curve numbers for hydrologic soil-cover complexes (Antecendent moisture condition II, and Ia = 0.2 S).

Land use	Treament or practice	Hydrologic condition	Hydrologic soil group A	B	C	D
Pasture		Poor	68	79	86	89
or range		Fair	49	69	79	84
		Good	39	61	74	80
	Contoured	Poor	47	67	81	88
	"	Fair	25	59	75	83
	"	Good	6	35	70	79
Meadow		Good	30	58	71	78
Woods		Poor	45	66	77	83
		Fair	36	60	73	79
		Good	25	55	70	77

The hydrologic condition can be determined by using vegetative condition and air-dry weight of the cover (NEH-4 Tables 8.1 and 8.2). The appropriate Hydrologic Soil Group (HSG) can be determined by several procedures. Table 7.1 in NEH-4 presents a list of over 4,000 soils giving the HSG. The SCS Soils-5 file, put in an interactive soils information system by the U.S. Army Corps of Engineers (1983) also lists the HSG for particular soil. Brakensiek et al. (1984) presented a method to estimate the HSG from textural composition.

2.2.2 The statistical approach

While values of CN are usually estimated from tables based on soils and vegetation, it is also possible to determine an actual CN from rainfall and runoff data. This is possible through solution of equation 5 for S to

$$S = 5(P+2Q-(4Q^2+5PQ)^{1/2}) \qquad [7]$$

thus defining an S (and therefore a CN via equation 6) from any P-Q pair. Some division exists in the literature on the number and kind of data required to define a consensus CN for a watershed. Two types of P-Q pairs can be used for the CN calculation, the natural events or the ordered data, where the P and Q sets both in an ordered array are matched up, with equation 5 merely transforming the P vector to the Q vector. The last method was presented by Hjelmfelt (1980) and preserves the original intended use of the method to predict a given return period Q from that same return period P.

In this study three methods of CN determination are used in the analysis.

1. Mean; curve numbers for all the events are calculated and the arithmetic mean is taken.
2. Non-linear regression; the optimum curve, describing the two parts of equation [5], is fitted through the P-Q pairs using a non-linear regression algorithm.
3. Relative storm size; only the large rainstorms are selected for this analysis, using a selection criterion which is described below.

For all three methods both the natural and ordered data were used as input, thus producing a total of six CNs per watershed. The computational procedures or each method are given in section 3.1.

The third method was developed because small storms tend to bias the relationship towards an overestimated CN. Smith and Montgomery (1980) and

Hjelmfelt (1982) suggested that "small" events should be eliminated from the data set. However, on a very porous forested watershed of CN = 40, a storm of three inches would be "small" while for a near impervious parking lot of CN = 99, virtually any rainstorm would be "large". Obviously there is a need for a relative storm size definition. In order to obtain an unbiased storm size, equation [5] is easily put into dimensionless form by dividing by S, thus yielding

$$Q/S = (P/S - 0.2)^2/(PS+0.8), \quad (P/S > 0.2) \qquad [8]$$

$$Q/S = 0 \quad , (P/S \leq 0.2$$

The S values corresponding to the CN (in the three AMC) are found to present a close correlation (Hawkins, et al., 1984):

$$S_I = 2.281\ S_{II} \qquad [9]$$

and

$$S_{III} = 0.427\ S_{II} \qquad [10]$$

This leads us to the following rainfall runoff equations

AMC III : $Q/S_{II} = (P/S_{II} - 0.085)^2/(P/S_{II}+0.342), \quad (P/S_{II} > 0.085) \qquad [11]$

$Q/S_{II} = 0 \quad , (P/S_{II} \leq 0.085)$

AMC I $Q/S_{II} = P/S_{II} - 0.456)^2/(P/S_{II}+1.84) \quad , (P/S_{II} > 0.456) \qquad [12]$

$Q/S_{II} = 0 \quad , (P/S_{II} \leq 0.456)$

The equations [11] and [12] are shown in Figure 4, which illustrates CNs in dimensionless form for three AMCs.

A broader interpretation of the AMC categories is as "error bands" or envelopes, indicating the experienced variability in rainfall-runoff relationships. Hjelmfelt et al. (1981) found that established AMC relationships fairly accurately described the 10 percent, 50 percent, and 90 percent cumulative probability of the runoff depth for a given rainfall via

the CN method, corresponding to AMC III, II, and I respectively. An illustration is given in Figure 5.

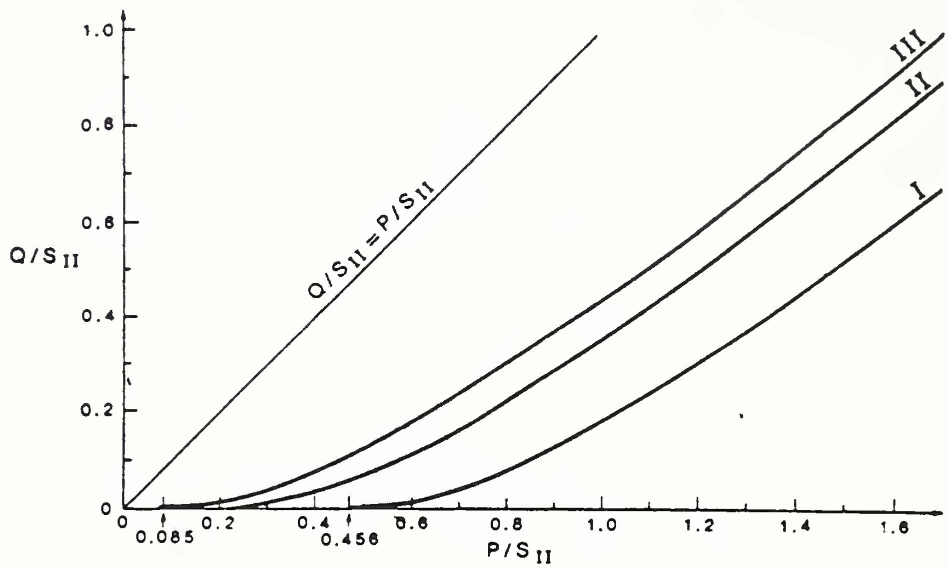

Figure 4. Dimensionless rainfall-runoff relationships for three antecedent moisture conditions.

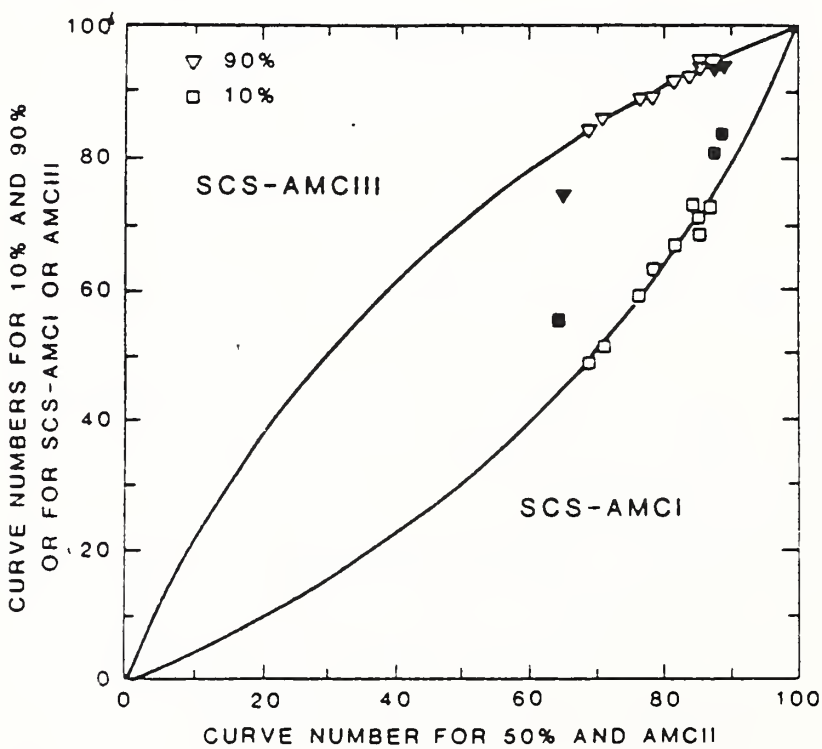

Figure 5. Probabilities associated with AMC categories.

Thus equations [11] and [12] have associated runoff probabilities which are shown in Table 3.

Table 3. Runoff probability for P/S*

P/S	Prob(Q/S 0)	Comments
0	0	
0.085	0.10	AMC III
0.20	0.50	AMC II
0.456	0.90	AMC I
	1	

*S defined on AMC II

An extensive description of this selection method is in Appendix 1. In this paper the criterion P/S > 0.456, or Prob (Q/S > 0) = 0.90 is selected to present a large event, where S is defined on AMC II.

The elimination of small and medium events (Appendix 1) from the data set is an iterative procedure in which the average S_{II} is calculated, the smallest event is dropped if it does not meet the selection criterion, a new S_{II} is calculated, and so forth until only large events are left in the set. From the remaining data, the average CN is calculated.

The disadvantage of this P/S "selection" method is that it does not always produce a CN, particularly in arid regions, because all the events are classified as "small" and therefore left out. Since of the two remaining techniques the regression method is the closest to the P/S "selection" method, especially when calculated from ordered P and Q arrays, this method seems the

most appropriate for the purpose of this study. Illustration of this decision and examples of the hydrologic data manipulation are presented in section 3.1.

2.3 Landsat images

The first Earth Resources Technology Satellite, which is now called Landsat 1 was launched on July 23, 1972. Following Landsat 1 four more Landsats have continued the program. The satellites circle the globe in a circular, near polar orbit so that the same point on the Earth's surface is viewed every 18 days at the same time of day. Landsats 1-5 all carried a high resolution sensor, the multispectral scanner (MSS). The Landsat MSS, operating in the visible and near infrared wavelengths, continually scans the earth in a 185-km swath nominally perpendicular to the satellite orbital track. The location of visible and infrared radiation in the spectrum of electromagnetic wavelengths is given in Figure 6. Scanning is accomplished in the cross-track direction by an oscillating mirror. The forward motion of the satellite provides the along-track progression of the scan lines. For each mirror sweep, six adjacent lines are scanned simultaneously in each of the four spectral bands of the electromagnetic spectrum. These four bands are:

1. Band 4, the green band, which covers the wavelengths between 500 and 600 nanometers (nm = 10^{-9}m). This band responds to reflected radiation from sediment-laden and shallow waters.
2. Band 5, the red band, between 600 and 700 nm. This band responds to man-made features such as urban and rural settlements.
3. Band 6, a near infrared (IR) band, between 700 and 800 nm. This band responds to vegetation and landforms.

4. Band 7, another near IR band, between 800 and 1100 nm. This band also responds to vegetation, land forms, water, and provides the best haze penetration.

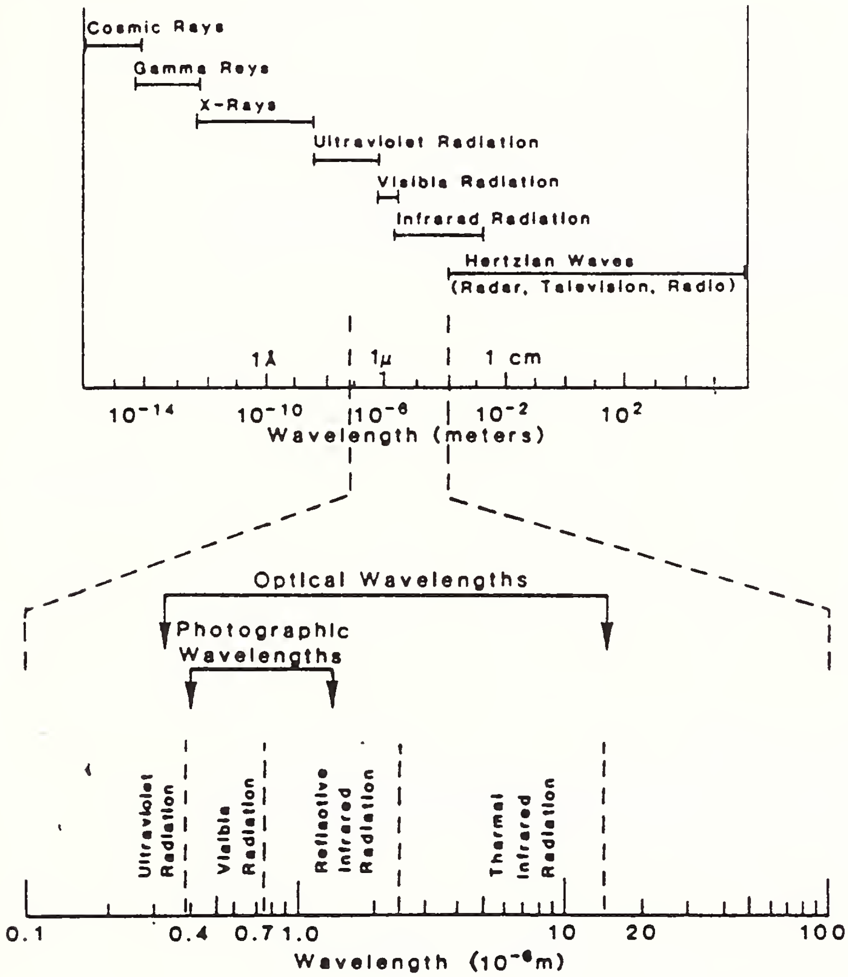

Figure 6. The electromagnetic spectrum.

The Landsat data are distributed in sections called "scenes". Each scene is approximately 185 km wide by 185 km long. Each digital picture element (pixel) is 57 m wide by 79 m long. The Landsat computer compatible tapes (CCT's) contain the measured radiance response values in the four bands for each pixel in the scene. The components of Landsat scenes are illustrated in Figure 7. The rows of pixels are referred to as "scan lines" and the columns

are referred to as elements. The lines are numbered consecutively from north to south and the elements are numbered from west to east.

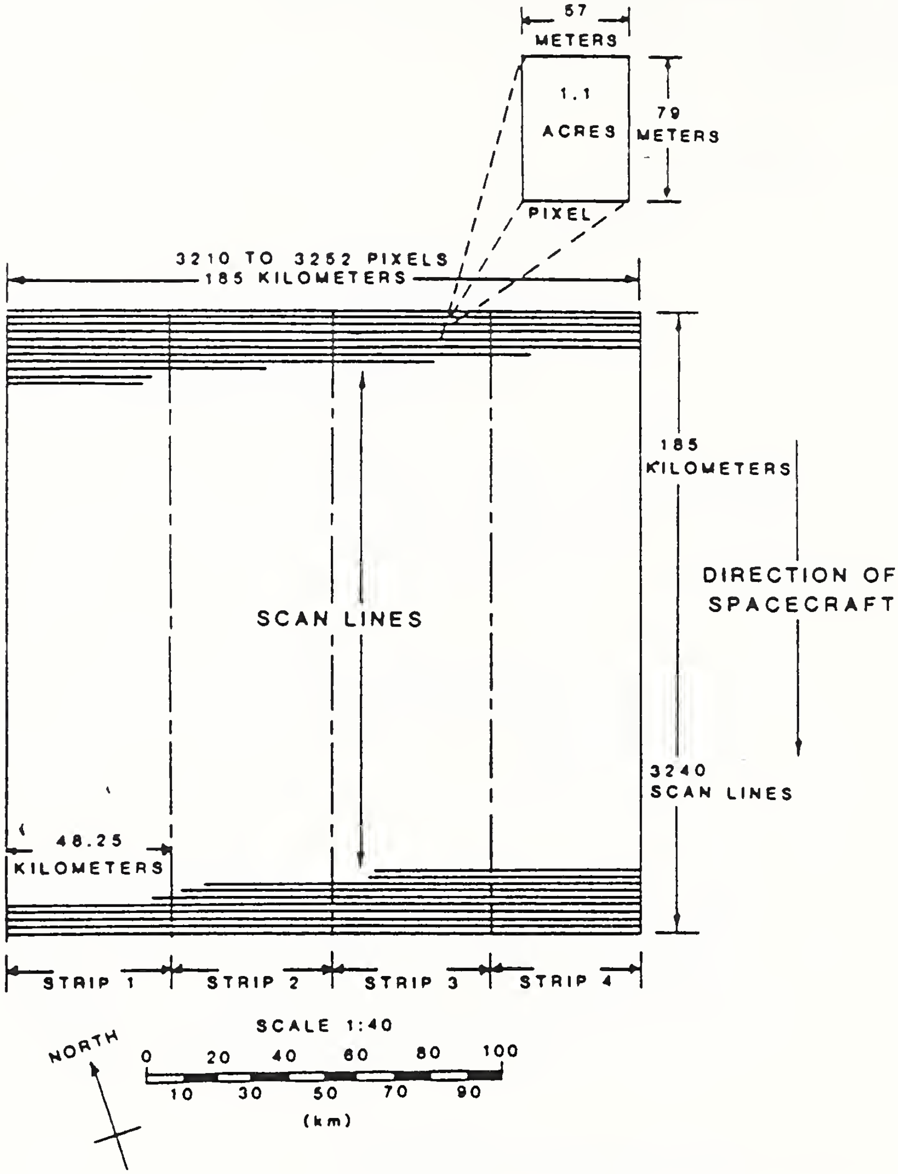

Figure 7. Landsat scene components.

Pattern recognition to distinguish land cover with Landsat MSS is based on the premise that each land cover type has a specific range of spectral responses in one or more channels. To illustrate the possibility of discrimination by comparison of the responses in different wavelength bands,

the typical relative response curves for vegetation, soil, and water are given in Figure 8. Figure 9 illustrates the principle of a MSS classifier. The categories from Figure 8 are plotted in a measurement space whose axes are their band 5 and band 7 responses. In reality there is not such a unique measurement pattern associated with each category. Rather, associated with each category is a probability distribution, due to natural random variations, systematic seasonal causes, atmospheric conditions, etc. In section 3.2 a number of MSS band combinations are described as well as the cover materials that they emphasize.

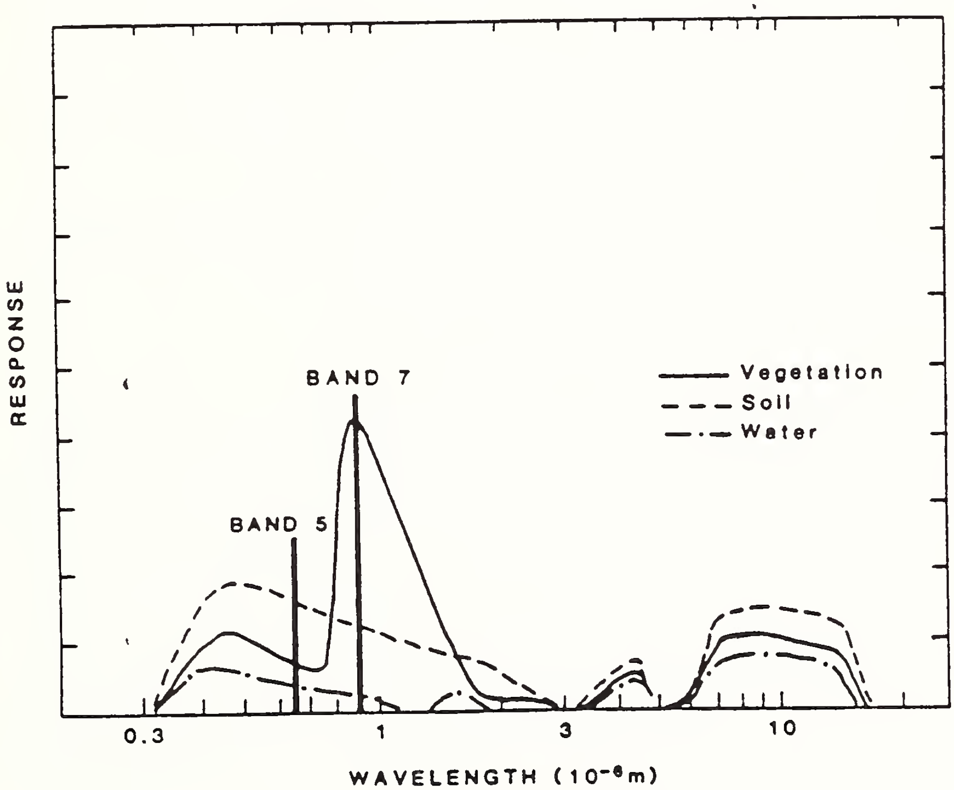

Figure 8. Relative response curves.

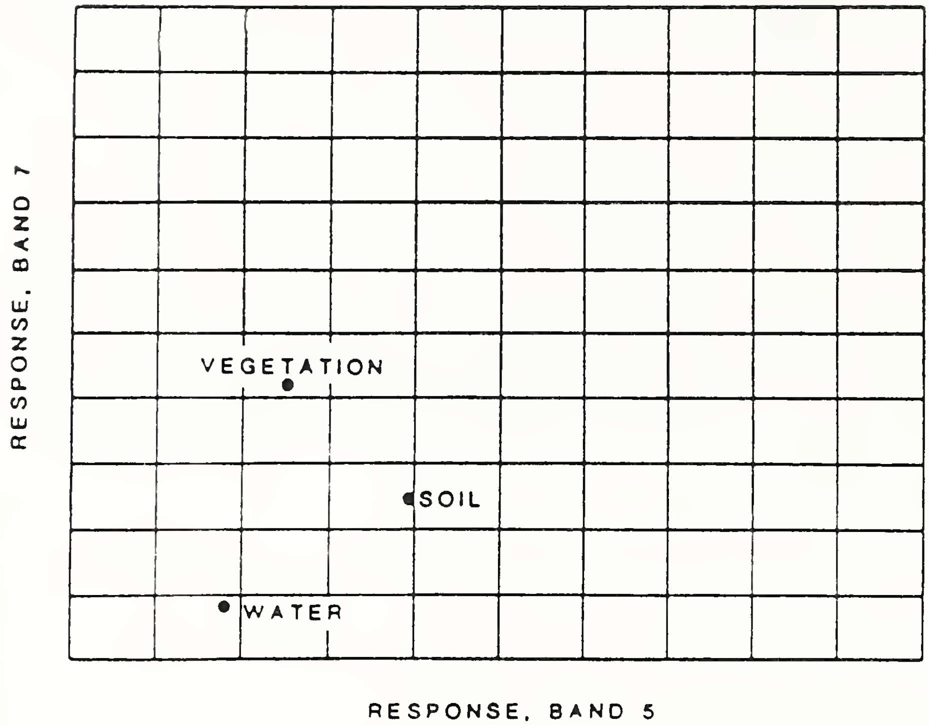

Figure 9. The categories vegetation, soil, and water, and their responses in bands 5 and 7.

A great deal of this Landsat analysis was performed using the Office for Remote Sensing of Earth Resources (ORSER) of Pensylvania State University computer software package described by Borden, et al. (1975). The ORSER software provides substantial capabilities for analyzing and classifying multispectral scanner data. The ORSER software package is fully operational on the U.S. Department of Agriculture (USDA) IBM 370 computer system operated by the Washington Computer Center (WCC). From a total of approximately 40, the ORSER programs that were used in this analysis are summarized below.

TPINFO Outputs information about contents of an original multispectral image data tape or SUBSET data tape. The information of interest in the Identification (ID) number, the table of contents, the data of exposure, and the sun elevation angle.

SUBSET Allow the user to specify the subscene he is interested in and to write it onto another tape. This increases tape processing efficiency and reduces computation cost.

SUBGM Version of SUBSET that is used to geometrically correct, rotate, and scale Landsat data during extraction of a subject.

NMAP Creates a printed grey scale brightness map which shows the overall scene (or SUBSET) features. The program assists the user in recognizing and visually correlating the data on tape to, either SUBSET or SUBGM, with areas seen on photographic imagery or on topographic maps.

STATS Computes and outputs statistics such as the means and standard deviation of the digital numbers, correlation matrices, and frequency histograms for specified areas and channels.

STATS2 has in addition the capability of producing two dimensional histograms of the responses of two spectral channels has been added.

PPD Classifies data using parallelpiped algorithm. The spectral characteristics of classes are defined by upper and lower bounds for each channel.

CLUS Unsupervised classifier which develops a set of spectral signatures by clustering.

CLASS Performs supervised classification using the Euclidean distance algorithm. The CLASS routine was modified to allow the output of raw Landsat data (digital numbers) to disk or tape. This version is called CLDISK.

Both the STATS2 and the CLDISK programs are only available on the USDA computer. Correction, calibration and further analysis of the Landsat data is performed on the WCC's IBM 370 computer using the Statistical Analysis System

(SAS) of SAS Institute Inc. (Helwig and Council, 1979). Examples of the above programs and their outputs are given in the Appendices 2 and 3.

3. Preparation of data

3.1 Curve numbers and watersheds

Rainfall and runoff records were obtained for 90 watersheds in the western USA from various sources, such as the United States Geological Survey (USGS), United States Forest Service (USFS), USDA-ARS, and others. The USDA-ARS data were retrieved from the Water Data Bank on the USDA Washington Computer Center (WCC) utilizing the REPHLEX procedures described by Thurman, et al. (1983). For each watershed the curve numbers were computed using three different methods and two input data arrangements. Thus a total of six CN were determined per watershed. The computational procedures for each method are given below.

Mean	Curve numbers for all the events are computed and the arithmetic mean is taken.
Non-Linear regression	Equation 5 and 6 of section 2.2 result in the relationship.

$$Q = (P+2-200/CN)^2/(P-8+800/CN), \quad P > (200/CN)-2 \qquad [13]$$
$$Q = 0 \qquad\qquad , \quad P \leq (200/CN)-2$$

Equation 13 is used in an algorithm that fits the general model through all the points and finds the optimum CN, i.e. the CN for which the sum of squares of deviations is smallest, or where $(Q-Q)^2$ has a minimum.

Relative storm size — Found by trial-and-error on the computer, using the following procedure.

1. Calculate average S of the events and take the smallest rainstorm.

2. Check if it meets the criterion $P/S_{av} > 0.46$.

3. If $P/S_{av} \leq 0.46$, drop this event, and go back to step 1.

4. Take the mean CN of the events left in the data set.

These computations were carried out for 90 watersheds, and the results are presented in Appendix 4. Sample SAS and FORTRAN programs to prepare and analyse the hydrologic data are displayed in Appendix 5.

Unfortunately, for 16% of the watersheds the selection method did not come up with a CN for the ordered P and Q arrays. For the remaining 70 watersheds which yielded a CN, the CN using the "mean" method is on the average 3.7 CN higher than the "selection" method, for the ordered data sets, while the "regression" method was only 0.2 CN higher. Thus although the CN computation using only large storms is theoretically more correct than a least squares fit, in practice there is very litle difference between the results of the two methods. This is why the non-linear regression method is selected for further use in this study. Table 4 shows the average CN for the different methods, including only the 70 watersheds for which a CN could be calculated using the selection method on natural and ordered events. Figure 10 visualizes the differences between the various average CN, and Figure 11 illustrates the CN found by non-linear regression for Chickasha R5 using both the natural and the ordered events.

Table 4. Average curve numbers for different calculation methods

Method	Data arrangement	
	Natural	Ordered
Mean	83.8	83.0
Non-linear regression	78.6	79.5
Relative storm size	77.9	79.3

A selection of basins for the initial study was made from all 90 watersheds available based on the following criteria :

1. the size has to be at least 20 acres (preferably 50 acres) to facilitate location on Landsat tapes.
2. there should be a wide range in CN.
3. variation in land cover type.
4. location in various parts of the West.
5. Landsat tapes should be readily available for immediate analysis (i.e., no long waits for tape orders).

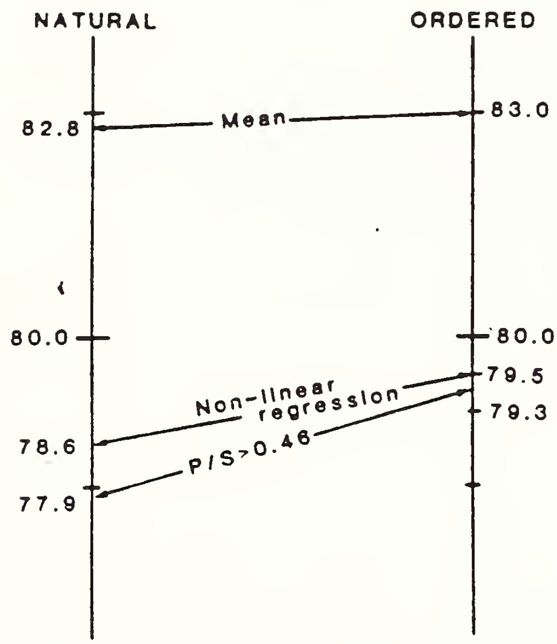

Figure 10. Results of the different CN methods.

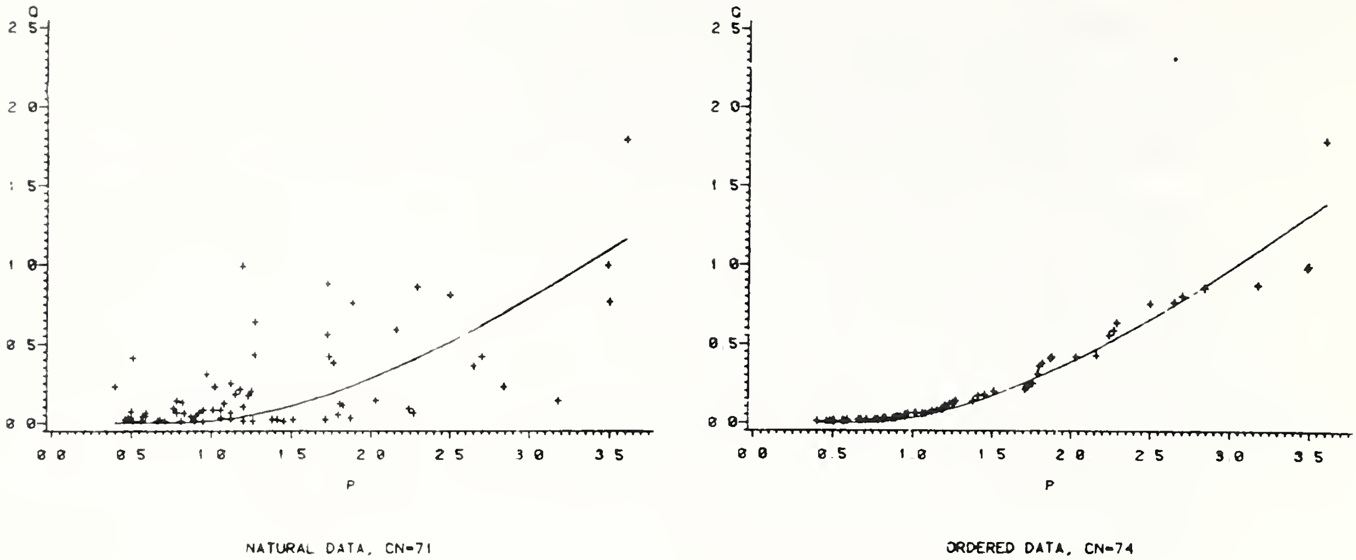

Figure 11. Non Linear regression for Chickasha R5 data using both natural and ordered P-Q data.

The watersheds meeting these criteria are listed in Table 5. The location of the watersheds is pictured in Figure 12.

3.2 Landsat response

3.2.1 Sources

Landsat images were obtained from the tape library of the Remote Sensing Systems Laboratory (RSSL) at the University of Maryland's Department of Civil Engineering and from files at the Hydrology Laboratory. The scenes were all originally purchased from the Earth Resources Observation Systems (EROS) data center in Sioux Falls, SD. Table 6 identifies the tapes used in the analysis.

Table 5. Summary of Watershed Characteristics

WATERSHED	State	Size(ac)	COVER	CN	Source of data	Period of data collection
Tombstone W4	AZ	560	Desert shrubs, grass	79	ARS	1959-1974
Chickasha R5	OK	27.7	Native grass, good cond.	74	ARS	1967-1977
Chickasha R6	OK	27.2	Native grass, good cond.	74	ARS	1967-1977
Chickasha R7	OK	19.2	Pasture, poor cond.	85	ARS	1967-1977
Chickasha R8	OK	27.6	Pasture, fair cond.	80	ARS	1967-1977
Halfway Creek	UT	484	Hardwoods, brush, grass	64	USFS	1940-1965
Morris Creek	WY	156	Hardwoods, conifers, grass	62	USFS	1940-1965
Dugout Creek	WY	518	Desert shrubs	93	USGS	1965-1972
Frank Draw	WY	506	Desert shrubs	87	USGS	1982-1983
W.F. Dry Cheyenne	WY	442	Desert shrubs	90	USGS	1965-1973

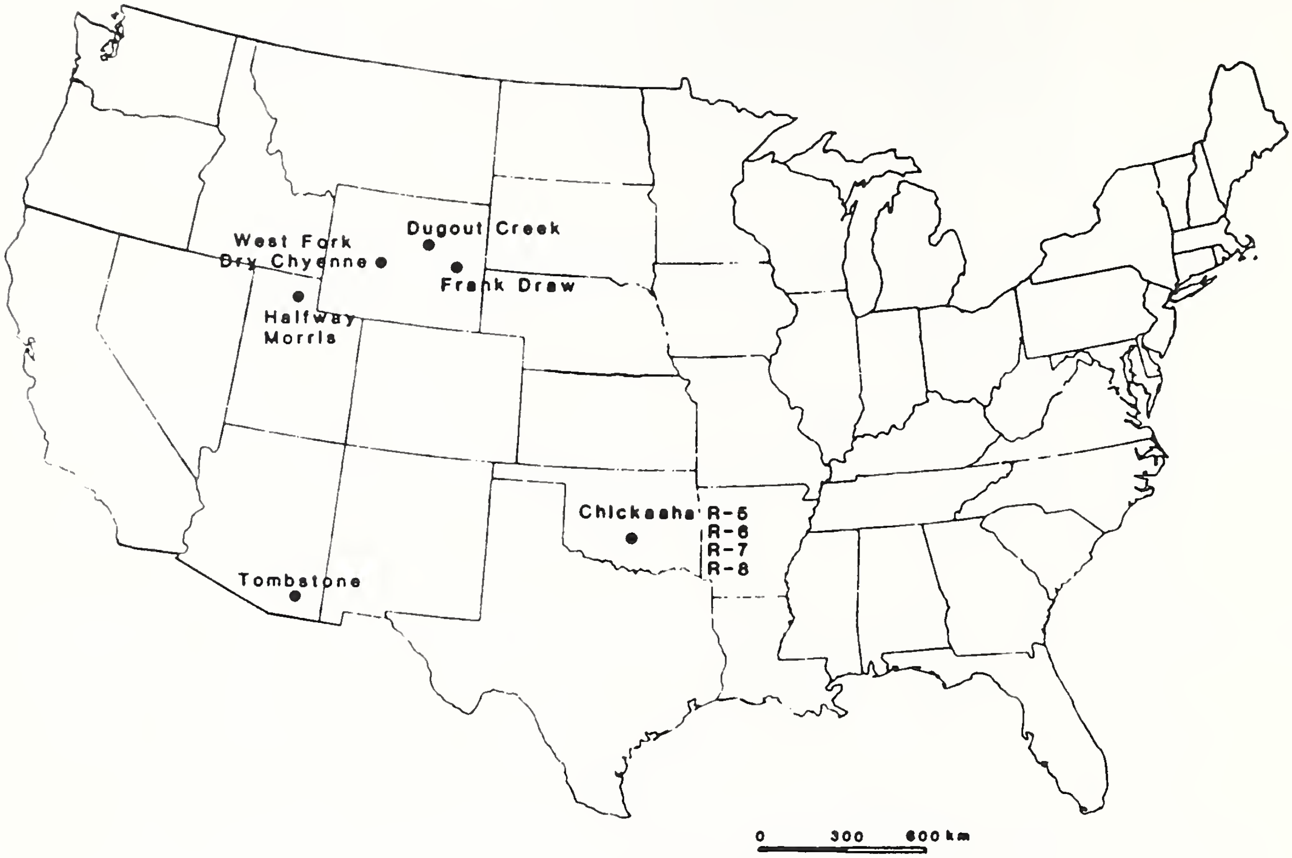

Figure 12. Location of the watersheds selected.

3.2.2 Mapping and data retrieval procedures

The watersheds that have been selected in section 3.1 were located on USGS 1:24,000 and 1:250,000 scale topographic maps and (if available) on aerial photographs. For an initial look at the scenes use was made of an image display system at the RSSL. The image processing system utilized was an International Imaging System, model 70F, interfaced to a Digital PDP 11/24 RSX - 11M operating system. The results of processing were displayed on a Mitsubishi 512 x 512 pixel color monitor. Comparing the color display and the topographic maps, the watershed boundaries were roughly described in terms of their line and element numbers. Using this information from the RSSL system a

Table 6. Tape information

Watershed	Path-Row	Scene ID	Date of observation
Tombstone W4	38-38	10984-17093	03 APR 75
Halfway and Morris	41-32	20155-17310	26 JUN 75
Dugout Creek	38-30	11416-16394	08 JUN 76
Frank Draw	37-30	11073-16554	01 JUL 75
West Fork Dry Cheyenne	39-30	20153-17184	24 JUN 75
Chcikasha R5, R6, R7 and R8	30-36	1256-16415	05 APR 73
		1400-16402	27 AUG 73
		1508-16383	13 DEC 73
		1706-16332	29 JUN 74
		1814-16295	15 OCT 74

SUBSET was made of the general area and was visualized by a line printer map (NMAP- procedure). Subsequently a PPD program, using the rather unique response pattern of open water, was performed on the same SUBSET area, thus creating a line printer map that only indicates lakes, farm ponds, etc. This map plus the detailed information from the topographic maps and aerial photographs was sufficient to accurately indicate watershed boundaries on the line printer map. An example of the location of a watershed is presented in Appendix 6. The digital numbers (DN) within the watershed boundaries were written to disk files by means of the CLDISK program.

3.2.3 Correcting and calibrating procedures.

Landsat digital images are commonly analyzed by using the digital numbers (DN) for each pixel. Although this procedure may be satisfactory when only a single, internally consistent image is used, in the case of this study the procedure would produce incorrect results, since the DN were collected by different satellites and at different times. Therefore, the DN should be converted to dimensioned equivalents such as radiance and reflectance. The digital levels are related by a linear model (calibration) to the intensity of reflected radiant energy that are not directly comparable among the Landsat satellites because of differences in the calibration of their multispectral scanner (MSS) instruments. In addition, comparison or combinations of images taken at different times requires correction for different angles of solar illumination.

The radiance as measured at the satellite in a single band is calculated by

$$\text{Radiance} = DN/Dmax\ (Lmax - Lmin) + Lmin \quad (mW.cm^{2-}sr^{-1}) \qquad [14]$$

where

DN = the digital value of a pixel from the CCT (-)

Dmax = the maximum digital value of that band (-)

Lmax = radiance measured at detector saturation ($mWcm^{-2}\ sr^{-1}$)

Lmin = the lowest radiance measured by detector ($mWcm^{-2}\ sr^{-1}$)

Table 7 gives the Lmax, Lmin, and Dmax values for Landsats 1, 2, and 3, and for different scanner calibrations at different times. It is modified from the Landsat Data Users Handbook (USGS, 1979, p AE-16) and Robinove et al. (1981). Although no Landsat-3 data were included in this analysis, the values are included for reference.

Table 7. Landsats 1, 2, and 3 detector response.

MSS band	Wavelength (10^{-6}m)	Lmin (mW/cm^2sr^{-1})	Lmax (mW/cm^2sr^{-1})	Dmax (-)
Landsat 1				
4	0.5-0.6	0	2.48	127
5	0.6-0.7	0	2.00	127
6	0.7-0.8	0	1.76	127
7	0.8-1.1	0	4.00	63
Landsat 2 (22 January 1975 to 16 July 1975)				
4	0.5-0.6	0.10	2.10	127
5	0.6.0.7	0.07	1.56	127
6	0.7-0.8	0.07	1.40	127
7	0.8-1.1	0.14	4.15	63
Landsat 2 (after 16 July 1975)				
4	0.5-0.6	0.08	2.63	127
5	0.6-0.7	0.06	1.76	127
6	0.7-0.8	0.06	1.52	127
7	0.8-1.1	0.11	3.91	63
Landsat 3 (5 March 1978 to 31 May 1978)				
4	0.5-0.6	0.04	2.20	127
5	0.6-0.7	0.03	1.75	127
6	0.7-0.8	0.03	1.45	127
7	0.8-1.1	0.03	4.41	63
Landsat 3 (after 31 May 1978)				
4	0.5-0.6	0.04	2.59	127
5	0.6-0.7	0.03	1.79	127
6	0.7-0.8	0.03	1.49	127
7	0.8-1.1	0.03	3.83	63

The reflectance, which is the percentage of radiance to irradiance, is calculated in a single band for a Lambertian surface by

$$\text{Reflectance} = {}^{\pi}/E \sin\alpha \left[DN/Dmax(Lmax-Lmin)+Lmin \right] (-) \qquad [15]$$

where

α = solar elevation, measured from the horizontal, as annotated on Landsat images.

E = average solar irradiance in mW cm^{-2} at the top of the atmosphere:

Band 4 = 17.70 mW cm^{-2}

Band 5 = 15.15 mW cm^{-2}

Band 6 = 12.37 mW cm^{-2}

Band 7 = 24.91 mW cm^{-2}

Solar irradiance may vary as much as 7% from aphelion to perihelion. However, for the normal range of surface reflectance, the variation in reflectance would be less than 1%. Other corrections, for atmospheric absorption, atmospheric scattering, and the radiance effects of nearby pixels (adjacency effects) have not been applied. Corrections for these factors could be done in a highly sophisticated manner, such as the use of radiosonde observations at the time of imaging, in order to determine the state of the atmosphere.

Because these required measurments were not available, atmospheric effects were not taken into account.

Four assumptions were made in the reflectance calculations:

1. the state of the atmosphere is the same for all scenes
2. the terrain surface is a Lambertian reflector
3. the average terrain slope is zero
4. the sun angle contribution to the scene brightness is uniform over the entire scene

The values of Table 7 in equation [15] give the following equations used to compute the reflectance for each pixel:

Landsat 1

Band 4 Reflectance $= (DN/289)/ \sin a$ [16]

Band 5 $= (DN/306)/ \sin a$ [17]

Band 6 $= (DN/284)/ \sin a$ [18]

Band 7 $= (DN/125)/ \sin a$ [19]

Landsat 2, before 7/16/75

Band 4 Reflectance $= 0.1775\ ((DN/63.50)+0.10)/\sin a$ [20]

Band 5 $= 0.2074\ ((DN/85.81)+0.07)/\sin a$ [21]

Band 6 $= 0.2540\ ((DN/95.49)+0.07)/\sin a$ [22]

Band 7 $= 0.1261\ ((DN/15.71)+0.14)/\sin a$ [23]

From the above calculations spectral reflectance patterns were constructed for the ten watersheds that were selected in section 3.1 using the June 74 scene for the Chickasha watersheds. These patterns are shown in Figure 13.

To illustrate that there is a probability associated with the response in each band, Figure 14 gives the distribution histograms in band 5 for three watersheds.

3.2.4 Reflectance index models

Variation in CNs between the various watersheds is caused by differences in factors such as 1) hydrologic condition of the surface; 2) soil characteristics; 3) climate; and 4) topography. These factors can not be measured directly by a remote sensing system. However, remote sensing tends to give an integrated result of the factors mentioned above.

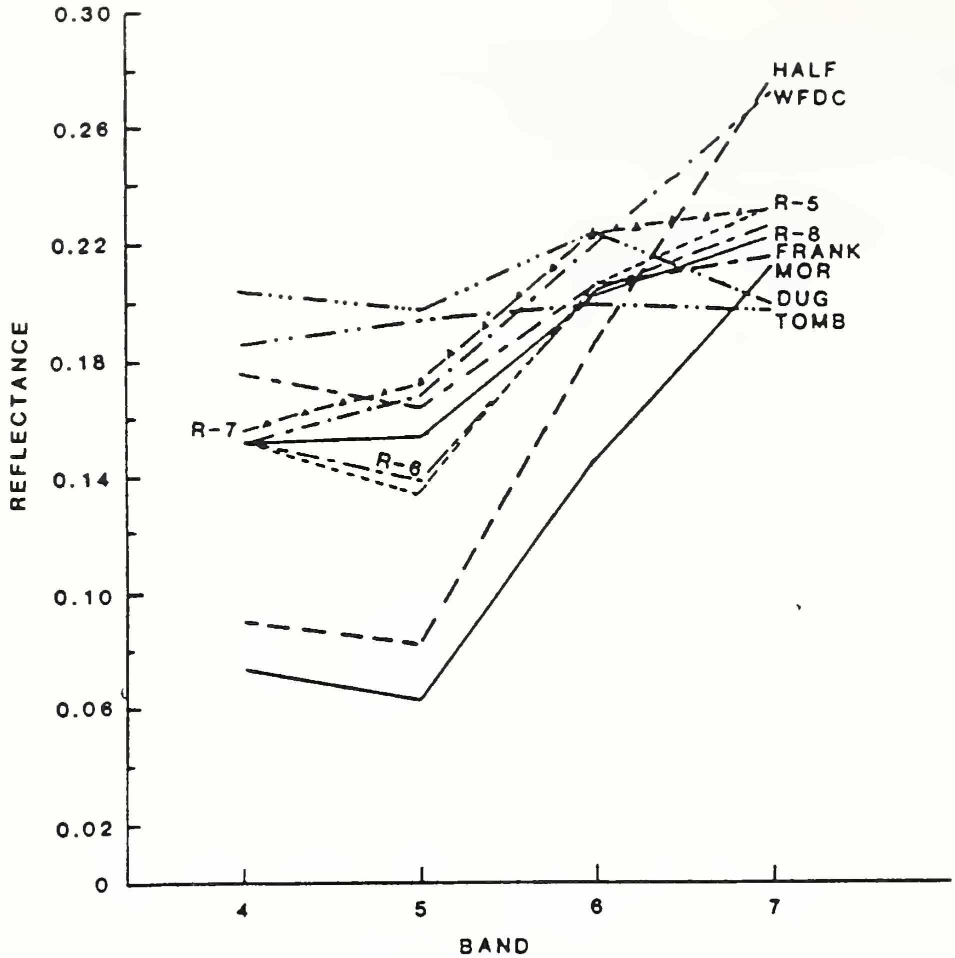

Figure 13. Spectral reflectance patterns for 10 watersheds.

The link between Landsat reflectance and CNs is made by presenting the multiband data in a single value, the reflectance index. The reflectance index is a quantity obtained directly or by ratioing, differencing, or otherwise transforming spectral data in a Reflectance Index Model (RIM), to represent plant canopy characteristics such as leaf area index, biomass, and percent cover, and soil properties. In the literature numerous RIMs are described and tested (Richardson and Wiegand, 1977; Jackson et al., 1980; Perry and Lautenschlager, 1984), and in this section a limited number of them will be summarized and employed in the CN study.

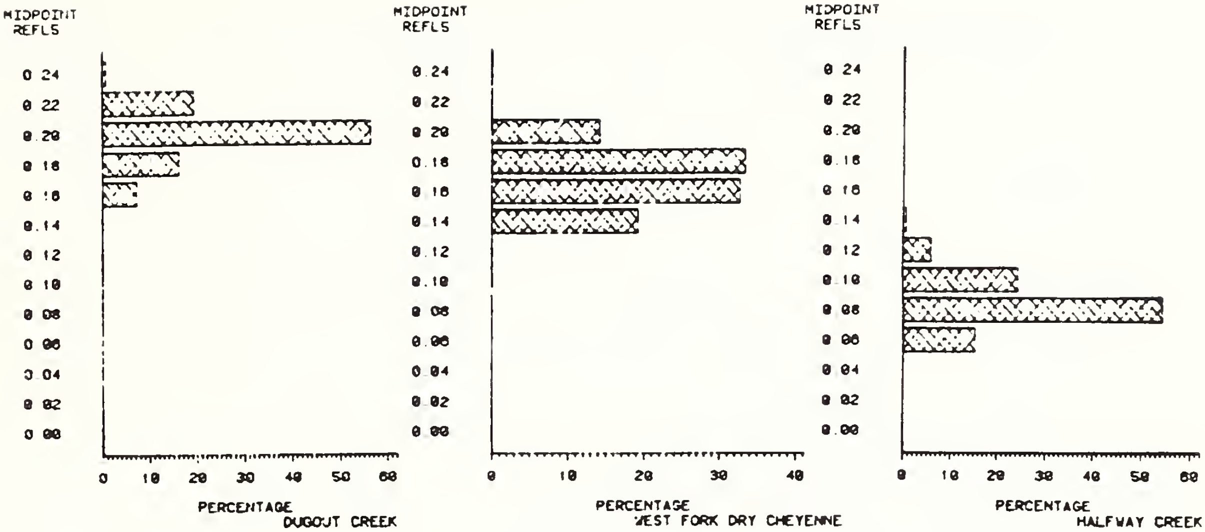

Figure 14. Comparison of the reflectance distributions in band 5 for three watersheds

The actual reflectance values from the MSS channels are used in the computations rather than the digital counts which can not be compared between the different scenes. Most formulae are based on ratios or linear combinations and exploit differences in the reflectance patterns of green vegetation and other objects as summarized in Figure 15.

Reflectance values from the individual channels (CH4, CH5, CH6, and CH7) have been used previously to estimate percent ground cover and vegetative biomass.

The ratio of reflectance values from two bands is a simple and useful vegetation index, if the bands are properly chosen. One criterion for choosing two bands for a ratio vegetation index is that the data from one band should decrease with increasing green vegetation, and data from the other band should increase with increasing green vegetation. This is the case for the red band and the near infrared bands, as can be seen from figure 15.

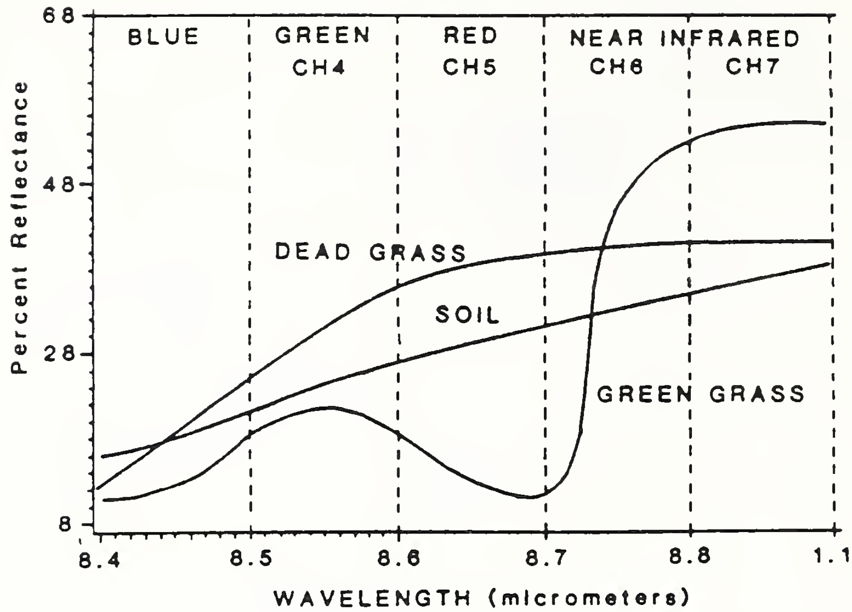

Figure 15. Idealized reflectance patterns of vegetation and soil.

In this study the following ratios are applied:

R54 = CH5/CH4 [24]

R65 = CH6/CH5 [25]

R75 = CH7/CH5 [26]

R65 and R75 have been shown to be sensitive to the amount of vegetation whereas R54 distinguishes best between soil and rock groups (Tucker, 1979; Eliason et al., 1981).

The ratio of the difference between values for two bands and the sum of the values for the two bands, the normalized difference (ND), is used for monitoring vegetation. This model was developed by Deering and Haas (1973) and discussed by Rouse et al. (1973). Deering et al. (1975) added 0.5 to ND to avoid negative values and took the square root of the result to stabilize the variance. This index is referred to as the transformed vegetation index

and will be denoted by TVI. Both ND and TVI were proposed using CH7, CH6, and CH5:

$$ND6 = (CH6 - CH5)/(CH6 + CH5) \quad [27]$$

$$ND7 = (CH7 - CH5)/(CH7 + CH5) \quad [28]$$

$$TVI6 = (ND6 + 0.5)^{1/2} \quad [29]$$

$$TVI7 = (ND7 + 0.5)^{1/2} \quad [30]$$

In addition to ratios and difference ratios, many other combinations of spectral bands have been used as reflectance indices. Kauth and Thomas (1976) have developed a technique, using vector analysis in four dimensional space to produce an orthogonal transformation of the original Landsat data space. They named the four new axes Soil Brightness Index (SBI), Green Vegetative Index (GVI), Yellow Vegetative Index (YVI) and non such (NSI):

$$SBI = 0.332\ CH4 + 0.603CH5 + 0.675CH6 + 0.262\ CH7 \quad [31]$$

$$GVI = -0.283\ CH4 - 0.660CH5 + 0.577CH6 + 0.388\ CH7 \quad [32]$$

$$YVI = -0.899\ CH4 + 0.428CH5 + 0.076CH6 - 0.041\ CH7 \quad [33]$$

$$NSI = -0.016\ CH4 + 0.131CH5 - 0.452CH6 + 0.882\ CH7 \quad [34]$$

Richardson and Wiegand (1977) used the perpendicular distance to the "soil line" as an indicator of plant development. The "soil line," a two dimensional analogue of the Kauth-Thomas SBI, was estimated by linear regression. Two perpendicular vegetation indices were proposed:

$$PVI6 = [(-2.507-0.457CH5 + 0.498CH6)^2 + (2.734 + 0.498CH5 - 0.543CH6)^2]^{1/2} \quad [35]$$

$$PVI7 = [(0.355CH7 - 0.149CH5)^2 + (0.355CH5 - 0.852CH7)^2]^{1/2} \quad [36]$$

The difference Vegetation Index (DVI), suggested as computationally easier than PVI7, is essentially a rescaling of PVI7 (Richardson and Wiegand, 1977):

DVI = 2.4 CH7 - CH5 [37]

The Ashburn Vegetation Index (AVI) was suggested by Asburn (1978) as a measure of green growing vegetation:

AVI = 2.0CH7 - CH5 [38]

3.2.5 Reflectance index models and ground truth.

Ground truth was collected at approximately the same time as the Landsat overpass for four of the five available scenes of the rangeland watersheds in Chickasha, Oklahoma. In the watersheds (R5, R6, R7, and R8) the following information was obtained: 1) a field estimate of the standing vegetation that is green matter; 2) fresh biomass (in grams per sample plot); and 3) dry biomass (in gm per sample plot).
Correlations (r) were made of ground truth, acquired from four watersheds at four different times (N = 16), with the 19 RIMs which are discussed above. The results are arranged in Table 8.

In general the percentage of green matter shows the highest correlations. Those RIMs using band 5 and 6 combinations correlate better with the ground truth information than the models that use band 6 and 7 combinations. Similar results were found by Richardson and Wiegand (1977).
Perry and Lautenschlager (1984) demonstrated that R65, ND6 and TVI6 are equivalent for decision making (and so are R75, ND7 and TVI7). This finding is again underlined by the closeness of the correlation coefficient for these RIMs.

Surprising is the high negative correlation of PVI6.

Table 8. Correlations between reflectance index models and ground truth

RIM	Green matter (%)	Fresh biomass	dry biomass
CH4	0.211	0.186	0.153
CH5	-0.310	-0.416	-0.441
CH6	0.375	-0.002	-0.046
CH7	0.369	0.001	-0.003
R54	-0.480	-0.581**	-0.591**
R65	0.780*	0.557**	0.551**
R75	0.619**	0.449	0.477
ND6	0.796*	0.545**	0.534**
ND7	0.626*	0.461	0.483
TVI6	0.801*	0.541**	0.529**
TVI7	0.627*	0.463	0.484
GVI	0.803*	0.396	0.388
SBI	0.117	-0.157	-0.190
YVI	-0.518	-0.648*	-0.652*
NSI	-0.442	-0.050	-0.034
PVI6	-0.801*	-0.293	-0.254
PVI7	0.594**	0.226	0.234
DVI	0.594**	0.226	0.234
AVI	0.627*	0.271	0.281

* Statistically significant at 0.01 probability level

** Statistically significant at 0.05 probability level

4. Results

4.1 Relationships between curve numbers and reflectance index models.

First a linear relationship was tested for the curve numbers and reflectance indices, which were derived as is explained in the previous chapter. Figure 16 shows the plots for R65 and SBI.

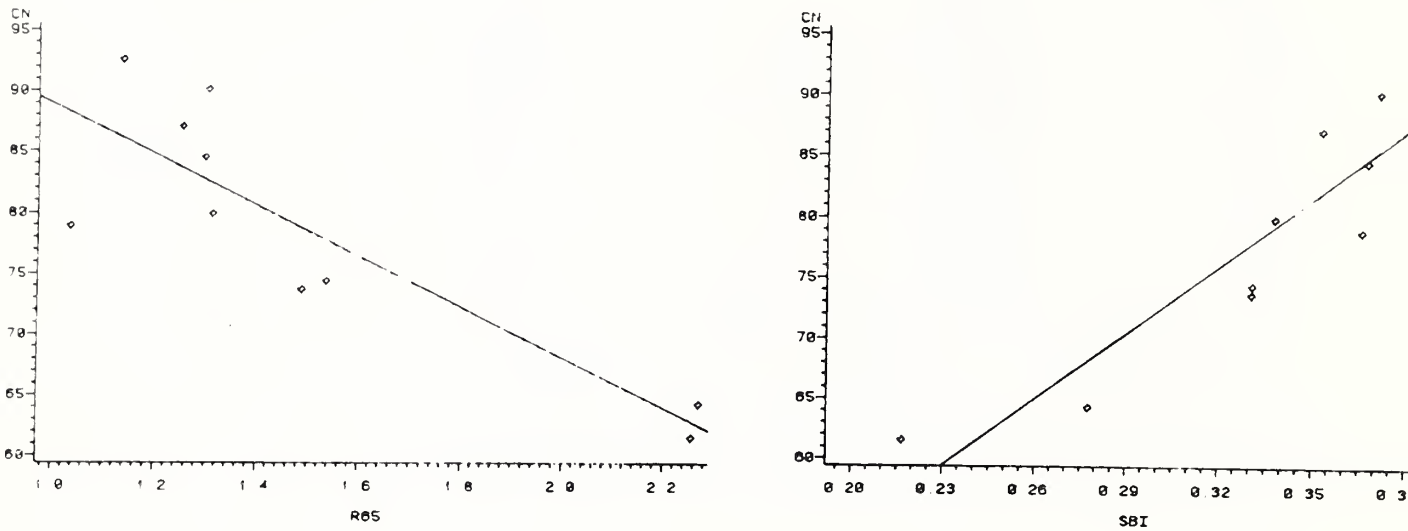

Figure 16. Linear relationships for curve numbers and two RIMs (N=10).

Correlations for all 19 RIMs and CNs were established and are given in Table 9.

Notable are the high values for the single channels 4, 5, and 6. Again the RIMs that consist of band 6 and 5 combinations give higher correlations than the band 7 and 5 combinatons. If we take only the band 6 and 5 combinations and the RIMs that show a correlation which is statistically significant at the 0.01 probability level, five RIMs remain. Descriptions of the relationships between these RIMs and CNs were established using linear

regression. The parameters (a1 and b1) of the general relationship

$$CN = a1 + b1\ (RIM)$$

and the correlation coefficient (r) belonging to it are given in Table 10. Also shown in table 10 are the parameters and correlations for the general equation

$$\ln CN = a2 + b2\ (RIM)$$

which suggests the exponential relationship

$$CN = a3 \times e^{b2\ (RIM)}$$

Table 9. Correlations between curve numbers and reflectance index models (N = 10)

RIM	r	RIM	r
CH4	0.854*	TVI6	-0.841*
CH5	0.899**	TVI7	-0.808*
CH6	0.851*	SBI	0.918**
CH7	-0.095	GVI	-0.705
R54	0.636	YVI	-0.674
R65	-0.865*	NSI	-0.077
R75	-0.840*	PVI6	0.685
ND6	-0.850*	PVI7	-0.524
ND7	-0.821*	DVI	-0.524
		AVI	-0.571

* Statistically significant at 0.01 probability level

** Statistically significant at 0.001 probability level

Table 10 indicates that an exponential relationship generally improves the fit, but probably not significantly.

Personal communication with Ken Renard, director of the Southwest

Rangeland Watershed Research Center in Tucson, (Arizona) cleared up the poor fit of the Tombstone watershed (CN = 79 in Figure 16). This watershed has a very high infiltration in the main channel. Thus it has generally a low discharge at the flow measurement structure and therefore an underestimated

Table 10. Parameters of linear and exponential relationships between curve numbers and reflectance index models.

RIM	linear			exponential		
	a1	b1	r	a2	b2	r
CH5	47.55	212.19	0.899	3.940	2.840	0.915
R65	109.56	-20.72	-0.865	4.774	-0.280	-0.888
ND6	91.33	-71.27	-0.850	4.528	-0.960	-0.870
TVI6	176.15	-118.85	-0.841	5.669	-1.599	-0.860
SBI	17.41	183.20	0.918	3.537	2.453	0.934

CN. The actual CN on the slopes would be an estimated 10-15 CN higher. Leaving this watershed out the data set, gives the following correlation coefficients.

Table 11. Correlations between curve numbers and reflectance index models (N = 9)

RIM	linear	exponential
CH5	0.967	0.976
R65	-0.927	-0.944
ND6	-0.950	-0.962
TVI6	-0.955	-0.965
SBI	0.938	0.950

The parameters of both the linear and exponential relationships are presented in Appendix 7.

4.2 Significance of seasonal fluctuation of Landsat data.

Figure 17 illustrates the seasonal fluctuation of the R65 and SBI for the Chickasha watershed R7. To find out what the effect of this seasonality is on the relationships shown in Table 10, R65 and SBI values from the Chickasha

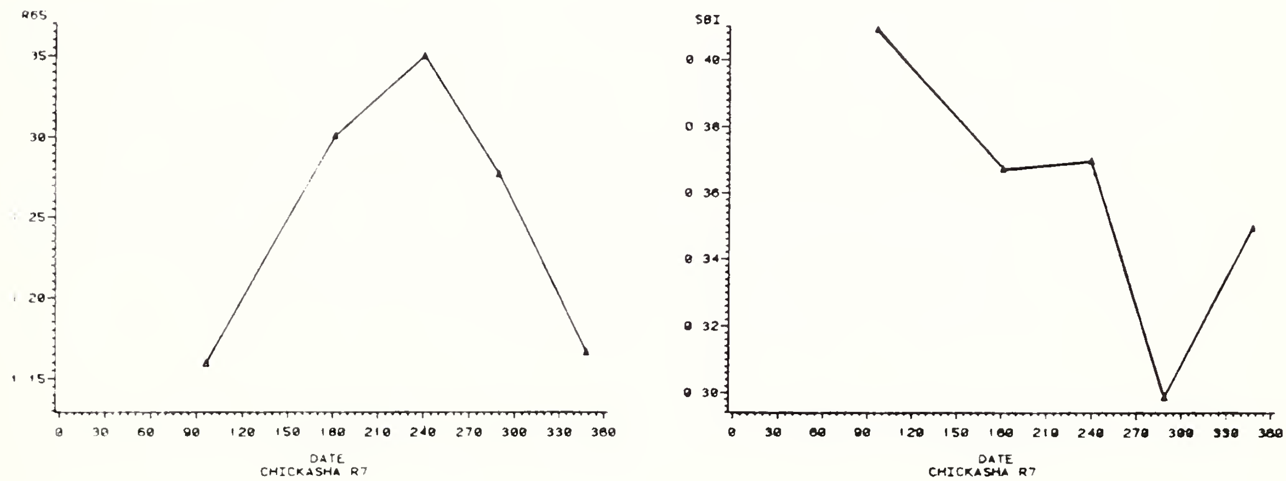

Figure 17. Seasonal fluctuation of R65 and SBI.

watersheds were calculated for five different times of the year and successively used in the linear regression. The correlation coefficients were calculated and are presented in Table 12.

Table 12. Correlation coefficients for two reflectance index models and curve numbers (N = 10).

RIM	April	July*	August	October	December
R65	-0.853	-0.865	-0.880	-0.896	-0.793
SBI	0.881	0.918	0.913	0.841	0.898

* from Table 10.

- Data from Chickasha watersheds vary over the year.

- Data from other watersheds are from April through June.

In Table 12 it can be seen that the use of reflectance data (in grassland watersheds) from different times of year for the Chickasha watersheds do not significantly change the correlation of a linear relationship. This indicates that the seasonal fluctuation of these RIMs could be relatively small as compared to the differences between the actual rangeland classes.

5. Conclusions and recommendations.

1. High correlations between rangeland runoff curve numbers and various reflectance indices obtained from Landsat MSS data resulted through regression analysis. Logarithmic transformations slightly improved the relationships. Discarding an anomalous basin in Arizona significantly improved the regression relationships.
2. Five reflectance indices were selected from a total of 19 originally calculated from the Landsat data because of their high correlations. Of these five indices, R65, ND6, and TVI6 provide virtually identical information on vegetation conditions. The other two indices, CH5 and SBI, provide information on soil background.
3. Although the "selection" method for determining CNs was preferred over the mean and regression methods, the regression method was chosen because it provided nearly similar results to the "selection" method and it is a lot less effort. Ordered data are used rather than the natural data because they result in a more stable CN value.
4. Future work should test the applicability of this method over a wider variety of rangeland conditions.

   -Test more basins.

   -Determine best season, if there is one.

   -Attempt to see if a combination of RIMs would provide even better CN estimation.

   -Evaluate other uses of this approach to SCS needs.

   -Based on all this, come up with a final methodology, of which an example is given in Figure 18.

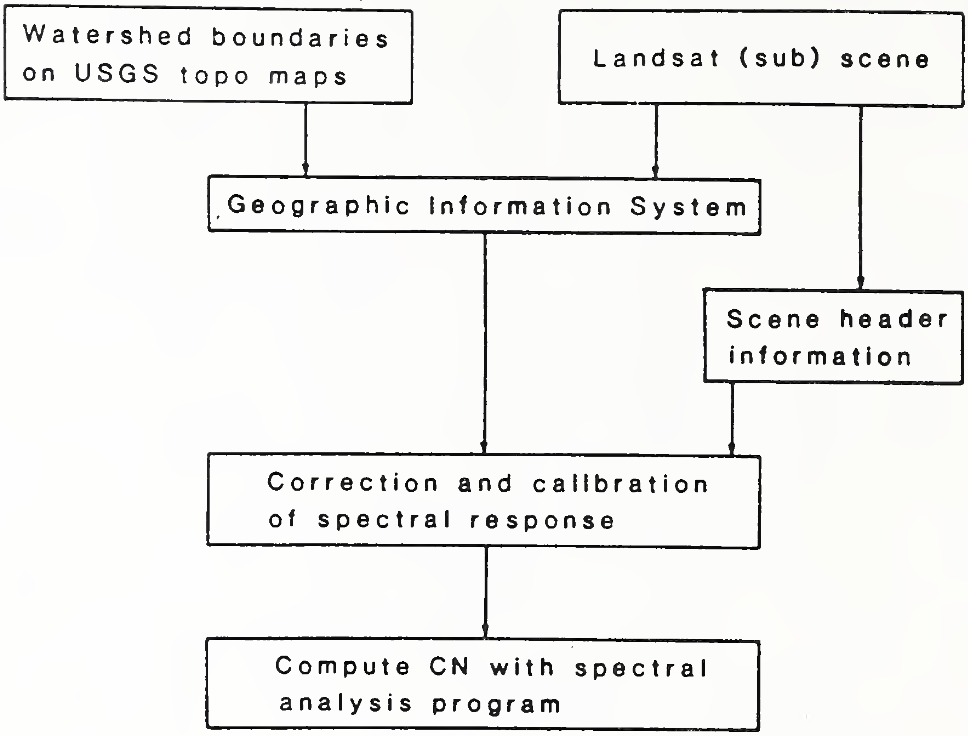

Figure 18. Outline for a computerized curve number estimation for rangeland.

A Geographic Information System (GIS) has the capability of integrating different sources of information related to geographicaly the same area. Various GIS's are available on the market. The spectral analysis program should incorporate the CN-RIM relationships.

Acknowledgement:

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REFERENCES

American Society of Photogrammetry. 1983.
Manual of Remote Sensing, Volumes I and II, second edition.

Blanchard, B. J 1973.
Measuring Watershed Runoff Capability with ERTS Data. Third Earth Resources Technology Satellite-1 Symposium (ERTS-1), Volume 1, Section B, NASA: 1089-1098.

Bondelid, T. R., T. J. Jackson, and R. H. McCuen. 1981.
A Computer Based Approach to Estimating Runoff Curve Numbers Using Landsat Data. AgRISTARS Techn. Rep. CR-R1-04040, USDA Hydrology Laboratory, Beltsville, MD.

Bondelid, T. R., T. J. Jackson, and R. H. McCuen. 1980.
Comparison of Conventional and Remotely Sensed Estimates of Runoff Curve Numbers in Southeastern Pennsylvania. ACSM-ASP Convention, St. Louis, MO.

Bondelid, T. R., T. J. Jackson, and R. H. McCuen. 1981.
Efficient Curve Number Estimation Using Digital Data Bases. Technical Papers of The American Society of Photogrammetry.

Borden, F. Y., B. J. Applegate, B. J. Turner, H. M. Lachowski, B. F. Merenbeck, and J. R. Hoosty. 1975.
Satellite and Aircraft Multispectral Scanner Digital Data Users Manual. ORSER-SSEL Technical Report 1-75, Office for Remote Sensing of Earth Resources, Pennsylvania State University, University Park, PA.

Brakensiek, D. L., G. R. Stephenson, and W. J. Rawls. 1984.
SCS Hydrology Procedures, USDA-ARS, unpublished.

Brown Fredericksen, M. E., V. J. Vogler, and J. D. Adams. 1983.
Estimation of Percent Vegetation for Range Management Using Landsat MSS Images. Renewable Resources Management, Proc. of the RNRF Symp. on the Appl. of Remote Sensing to Resource Management, Seattle, WA: 129-136.

Burford, J. B., J. L. Thurman, and R. T. Roberts. 1983.
Hydrologic Data for Experimental Agricultural Watersheds in the United States, 1974 (and previous years). USDA-SEA, Washington, D.C., Miscellaneous Publication No. 1937.

Deering, D. W., J. W. Rouse Jr., R. H. Haas, and H. H. Schell. 1975.
Measuring "Forage Production" of Grazing Units from Landsat MSS data. Proc. Tenth Int. Symp. on Remote Sensing of Environment, Univ. of Michigan, Ann Arbor, MI: 1169-1198.

Eliason, P. T., L. A. Soderblom, and P. S. Chavez. 1981.
Extraction of Topographic and Spectral Albedo Information from Multispectral Images. Photogrammetric Engineering and Remote Sensing, 11:1571-1579.

Frank, D. T. 1984.
Assessing Change in the Surficial Character of a Semiarid Environment with Landsat Residual Images. Photogrammetric Engineering and Remote Sensing, Vol. 50, No. 4: 471-480.

Haas, R. H. E. H. Horvath, and W. A. Miller. 1983.
Using a Digital Data Base for Inventory and Management of Public Rangeland. Renewable Resources Management. Proc. of the RNRF Symp. on the Appl. of Remote Sensing to Resource Management, Seattle, WA: 155-161.

Hawkins, R. H. 1984.
A Comparison of Predicted and Observed Runoff Curve Numbers. Water Today and Tomorrow, Proc. of the Specialty Conference Sponsored by the Irrigation and Drainage Division of the ASCE, Flagstaff, AZ: 702-709.

Hawkins, R. H., A. T. Hjelmfelt Jr., A. W. Zevenbergen. 1984.
Runoff Probability, Relative Storm Depth, and Curve Numbers. Submitted to the Journal of the Irrigation and Drainage Division of the ASCE on Nov. 16, 1984.

Helwig, J. T., and K. A. Council. 1979.
SAS Users Guide. 1979 Edition, SAS Institute Inc.

Hjelmfelt, A. T. Jr.. 1980.
Empirical Investigation of Curve Number Technique. Proc. ASCE 106 (HY9): 1471-1476.

Hjelmfelt, A. T. Jr., K. A. Kramer, and R. E. Burwell. 1981.
Curve Numbers as Random Variables. Water Resources Publications, Proc. Int. Sympt. on Rainfall-Runoff Modelling, Mississippi State University, Littleton, CO: 356-370.

Hjelmfelt, A. T. Jr. 1982.
Closure on "Empirical Investigation of Curve Number Technique". Proc. ASCE 108 (HY4): 614-616.

Jackson, R. R., P. J. Pinter Jr., R. J. Reginato, and S. B. Idso. 1980.
Hand-Held Radiometry. USDA-SEA, Agricultural Reviews and Manuals, ARM-W-191. Oct. 1980.

Kauth, R. J., and G. S. Thomas. 1976.
The Tasseled Cap - A Graphic Description of the Spectral-Temporal Development of Agricultural Crops as Seen by Landsat. Proc. Symp. Machine processing of Remote Sensing Data, LARS, Purdue, IN, IEEE Cat. No. 76, Ch. 1103-1, MPRSD.

Kraijenhoff van de Leur, D. A. 1973.
The Curve Number Method. ILRI Publ. 16, Vol. II (Drainage Principles and Applications): 281-285.

McGraw, J. F. and P. T. Tueller. 1983.
Landsat Computer-Aided Analysis Techniques for Range Vegetation Mapping. Journal of Range Management, 35(5). 1983.

Perry, C. R. J., and L. F. Lautneschlager. 1984.
Functional Equivalence of Spectral Vegetation Indices. Remote Sensing of Environment 14: 169-182.

Ragan, R. M., and T. J. Jackson. 1980.
Runoff Synthesis Using Landsat and the SCS Model Journal of the Hydraulics Division of the ASCE.

Rallison, R. E. and N. Miller. 1981.
Past, Present, and Future SCS Runoff Procedure. Water Resources Publications. Proc. Int. Symp. on Rainfall-Runoff Modelling, Mississippi State University,Littleton, CO: 353-364.

Richardson, A.J. and C. L. Wiegand. 1977.
Distinguishing Vegetation from Soil Background Information. Photogrammetric Engineering and Remote Sensing. 43:151-1552.

Robinove, C. J. 1982.
Computation with Physical Values from Landsat Albedo Difference Images. Remote Sensing of Environment, Vol. II:133-156.

Rouse, J. W. Jr., R. H. Haas, J. A. Schell, and D. W. Deering. 1973.
Monitoring the Vernal Advancement and Retrogradation (Green Wave Effect) of Natural Vegetation. Prog. Rep. RSC 1978-1, Remote Sensing Center, Texas A&M University, College Station, TX, NTIS No. E73-10693.

Schulze, R. E. 1982.
Generalizing the Use of the SCS Stormflow Model by Soil Moisture Budgeting. Proc. Int. Symp. on Hydrological Research Basins and their use in Water Resources Planning, Berne, Switzerland, Vol. 3:971-982.

Slack, R. B. and R. Welch. 1980.
SCS Runoff Curve Number Estimates from Landsat Data. Water Resources Bulletin, Vol. 16, No. 5:887-893.

Smith, R. E., and R. J. Montgomery. 1980.
Discussion on "Runoff Curve Number for Partial Area Watersheds." Proc. ASCE, 106 (IR4):6379-381.

Thurman, J. L., R. T. Roberts, and J. B. Burford. 1983.
Retrieval Procedures for Hydrologic Data from ARS Experimental Watersheds in the United States (REPHLEX). USDA-ARS Agricultural Reviews and Mannuals, ARM-NE-9, March 1983.

Tucker, C. J. 1979.
Red and Photographic Infrared Linear Combinations for Monitoring Vegetation. Remote Sensing of Environment, 8:127-150.

Tueller, P. T. 1980.
Remote Sensing for Range Management. Remote Sensing for Resource Management Conference, USDA-SCS and NASA, Kansas City, MO.

United States Army Corps of Engineers. 1983.
An Interactive Soils Information System User's Manual. Technical Report N-163, Champaign, IL.

United States Deprtment of Agriculture, Soil Conservation Service. 1972.
SCS National Engineering Handbook, Section 4, Hydrology. Washington, D.C.

United States Geological Survey, 1979.
Landsat Data Users Handbook (revised). USGS. Reston, VA.

Wood, M. K., and W. H. Blackburn. 1984.
An Evaluation of the Hydrologic Soil Groups as Used in the SCS Runoff Method on Rangelands. Water Resources Bulletin, Vol. 20, No. 3:379-389.

List of abbreviations and symbols

AMC	antecedent moisture class
AVI	Ashburn vegetation index
CCT	computer compatible tape
CH4	reflectance in channel 4
CH5	reflectance in channel 5
CH6	reflectance in channel 6
CH7	reflectance in channel 7
CN	runoff curve number
DN	digital number
Dmax	maximum digital value in a band
E	average Solar irradiance at top of atmosphere ($mWcm^{-2}$)
F	total acutal retention (in.)
GVI	green vegetative index
Ia	initial abstraction (in.)
Lmax	radiance measured at detector saturation ($mWcm^{-2}Sr^{-1}$)
Lmin	lowest radiance measured by detector ($mWcm^{-2}Sr^{-1}$)
MSS	multispectral scanner
N	number of data points
NEH-4	national engineering handbook, section 4
ND6	normalized difference, using bands 5 and 6
ND7	normalized difference, using bands 5 and 7
NSI	"non such" vegetation index
ORSER	office for remote sensing of earth resources
P	precipitation (in.)
PVI6	perpendicular vegetation index
PVI7	perpendicular vegetation index
Q	surface runoff (in.)
r	correlation coefficient
RIM	reflectance index model
R54	ratio of channel 5 over channel 4
R65	ratio of channel 6 over channel 5
R75	ratio of channel 7 over channel 5
S	maximum retention (in.)
SAS	statistical analysis system
SBI	soil brightness index
SCS	Soil Conservation Service
TVI6	transformed vegetation index
TVI7	transformed vegetation index
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WCC	Washington Computer Center
YVI	yellow vegetation index
α	sun elevation angle

Appendices

1. Runoff probability, relative storm depth, and curve numbers.

2. Examples of Job Control Language for the ORSER programs on the IBM 370 computer, and their outputs.

3. Examples of SAS programs used in the Landsat analysis.

4. Summary of curve number computations.

5. Examples of some SAS and FORTRAN programs used in the curve number analysis.

6. Location of Tomstone, W4 on line printer map.

7. Parameters of linear and exponential relationships between curve numbers and reflectance index models for 9 watersheds.

Appendix 1. Runoff Probability, Relative Storm Depth, and Curve Numbers

Richard H. Hawkins[1], M. ASCE, Allen T. Hjelmfelt, Jr.[2] M. ASCE,

and Adrian W. Zevenbergen[3]

Using existing antecedent moisture condition (AMC)--Curve Number relationships, a general expression of rainfall-runoff was developed for AMC I and AMC III. The distribution of the probability of event runoff exceeding zero is found to be approximately lognormal. Relative storm size is then proposed to be defined on the ratio P/S, where a "large" storm has P/S>0.46, when 90 percent of all rainstorms will create runoff. Consequent problems arising in the definition of CN from field rainfall-runoff data are discussed.

Background

The Curve Number Method is a widely used technique for estimating storm runoff depth from rainfall depth. It was pioneered and developed by the USDA-Soil Conservation Service (SCS). The primary source document for the method is their National Engineering Handbook, Section 4 "Hydrology", or for short "NEH-4" (14)

The basic equation is simply

$$Q = (P - .2S)^2/(P + .8S) \qquad (P>.2S) \qquad (1)$$
$$Q = 0 \qquad (P<.2S)$$

where Q and P are the runoff and rainfall depths and S is a linear index of watershed storage transformed to the index "Curve Number" by

$$CN = 1000/(10 + S) \quad \text{(S in inches)} \qquad (2)$$

$$\text{or} \quad CN = 25400/(254 + S) \quad \text{(S in mm)}$$

Curve numbers reflect the land condition, and tables and charts of CNs defined according to soil type, land use, cover, and watershed moisture status are given in numerous SCS and other agency documents.

The watershed antecedent moisture condition (AMC) is one of the most influential factors in determining CN. NEH-4 gives in its Table 10.1 conversions through three moisture classes, AMC I and AMC II, and AMC III, where condition II is the benchmark situation upon which a watershed is described, and condition I and III are the "dry" and "wet" situations. An abbreviated form of this relationship is given here at Table 1. NEH-4 also

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gives suggested approximate five-day antecedent rainfall depths necessary to achieve these three categories (which are not given here).

Table 1. Relationship Between CN and AMC Antecedent Moisture Class

I	II	III
100	100	100
87	95	98
78	90	96
70	85	94
63	80	91
57	75	88
51	70	85
45	65	82
40	60	78
35	55	74
31	50	70
22	40	60
15	30	50
9	20	37
4	10	22
-0-	-0-	-0-

Source: NEH-4, Table 10.1 (condensed)

Generalized Relationships

Equation 1 describes a family of storm runoff curves in the parameter S (or its tranform, CN). It is easily put into dimensionless form by standardizing on S, yielding

$$Q/S = (P/S-.2)^2/(P/S+.8) \quad (P/S>.2)$$
$$Q/S = 0 \quad (P/S<.2) \tag{3}$$

Also, the information on the AMC-CN relationship Table 1, may be abbreviated. The S values corresponding to the CNs (as given in Table 1 herein or NEH-4 Table 10.1) are found to present a close correlation:

$$S_I = 2.281\ S_{II} \qquad r^2 = 0.999 \quad S_e = 0.206 \text{ in} \tag{4}$$

$$S_{III} = 0.427\ S_{II} \qquad r^2 = 0.994 \quad S_e = 0.088 \text{ in} \tag{5}$$

The above equations pertain to the range $50<CN_{II}<95$, which encompasses most estimated and experienced CNs. Because Condition II is the reference status in Eqs. 1 and 3, substitution of $2.281S_{II}$ and $0.427S_{II}$ (Eqs. 4 and 5) into 3 leads to

$$Q/S = (P/S-0.085)^2/(P/S+0.342) \qquad P/S>.085 \tag{6}$$

$$Q/S = (P/S-0.456)^2/(P/S+1.824) \qquad P/S>.456 \tag{7}$$

where (6) and (7) yield AMC III and AMC I runoffs, and S is defined on AMC II. These three functions are shown in Figure 1.

For more clarity, the rainfall runoff equations may be grouped and written as:

$$Q_{III} = (P-.085S_{II})^2/(P+.342S_{II}) \qquad (8)$$

$$Q_{II} = (P-.2S_{II})^2/(P+.8S_{II}) \qquad (1)$$

$$Q_{I} = (P-.456S_{II})^2/(P+1.824S_{II}) \qquad (9)$$

In the above, the effective term rainfall (inside the parentheses in the numerator) must be positive. Q = 0 otherwise. Parenthetically, it should be noted here from equations 4 and 5 that

$$(S_I/S_{II}) \cong (S_{II}/S_{III}) \cong 2.28 \qquad (10)$$

Also, direct algebraic conversion of AMC is possible via Eqs. 1, 4, and 5. Substitution and simplification leads to

$$CN_I = \frac{CN_{II}}{2.281-0.1280\ CN_{II}} \qquad r^2 = 0.996,\quad S_e = 1.0\ CN \qquad (11)$$

$$CN_{III} = \frac{CN_{II}}{0.427+00.00573\ CN_{II}} \qquad r^2 = 0.994,\quad S_e = 0.7\ CN \qquad (12)$$

Equations 11 and 12 are similar to equations suggested previously by Sobhani (12) and are similarly derived.

Probability Descriptions

A broader interpretation of the AMC categories is as "error bands" or envelopes, indicating the experienced variability in rainfall-runoff relationships. In this role, site moisture per se acts as a surrogate for all other sources of variability, such as rainfall intensity, spatial variability of watershed or storm properties, or basic shortcoming in the structure and coefficients in Eq. 1. This role for AMC is found originally in NEH-4, and has been more recently elaborated by Rallison (7), Rallison and Cronshey (8), Rallison and Miller (5), and Springer et al. (13).

Hjelmfelt (5) found that the established AMC relationships fairly accurately described the 90 percent, 50 percent, and 10 percent cumulative probability of the runoff depth for a given rainfall via the CN method, corresponding to AMC I, II, and III, respectively. An illustration is given in Figure 2. Thus, equations 1 and 6 to 9 have runoff probabilities associated with them. For example, if at AMC I, there is then a 10 percent probability of runoff depth Q exceeding that indicated by equation 9. If say, $CN_{II} = 80$ and $P = 2$ inches, runoff expectations would then be:

90%: $Q>0.11$ in
50%: $Q>0.56$ in
10%: $Q>1.12$ in

where the above calculations were made from Eq. 9, 1, and 8, respectively.

This may be seen generally as a conditional probability distribution at a rainfall P with a mass on the P axis, for which Q = 0. This probability mass is the fraction of occurrences when the effective rainfall is zero, or when P is less than or equal to the initial abstraction.

This occurs when P<0.085S for condition III, when P<0.2S for condition II, and P<0.465S for condition I. From this reasoning, and obvious behavior at the extremes of $P = 0$ and $P = \infty$, Table 2 may be established.

A log normal distribution closely approximates Table 2, with a mean (μ_n) of -1.609 and standard deviation (σ) of 0.67. The transformation between AMC values can then be expressed in continuous and graphical form as shown in Fig. 3. Given the nature of the "data" from which this was derived, it should be considered approximate.

Table 2. Runoff Probability for P/S*

P/S	Pr(Q/S>0)	Comments
0	0	
0.085	0.10	AMC III
0.20	0.50	AMC II
0.456	0.90	AMC I
00	1	

*S defined on AMC II

Storm Size Perspectives

There is largely undocumented undercurrent of concern about the storm size requirements for application of the CN method. A main thread of the original intent was flood event design, and early development was through annual maximum daily rainfall and runoff data. This suggests some selection of larger events, though the precise scale of "largeness" eludes definition. Smith and Montgomery (11) claim that "P/S<0.4...poorly (if at all) define a CN in any case...", though they gave no reasons. Hjelmfelt (4) suggested that a "small" storm is one which "...P<0.2S where S is determined from the AMC I curve number," and cautioned users "... to eliminate small events from the data set." As developed in preceding sections this smallness threshold suggested by Hjelmfelt is P<0.456S, or Pr(Q/S>0) = 0.90, where S is defined on AMC II. In both of the above cases, the concern was determination of CN from field data, and in the latter case, possible biasing of the smaller scale data due to including only the events in which runoff occurred.

From the preceding development, it might be seen that Hjelmfelt's "small" storm is actually "large" in terms of runoff probability. Thus, the following classification is proposed, defining relative storm size on CN-based runoff probabilities.

Table 3. Relative Storm Sizes

P/S_{II} From	P/S_{II} To	Prob.$(Q/S_{II}>0)$ From	Prob.$(Q/S_{II}>0)$ To	Category
0	0.085	0	0.10	Very Small
0.085 -	0.20	0.10 -	.50	Small
0.20 -	0.456	0.50 -	.90	Medium
0.456 -	0.60	0.90 -	.95	Large
	>0.60		>0.95	Very Large

Using this as a guide, the user caution for CN determination from data could be recast as "use only large or very large events", or more precisely, "use only events for which $P/S_{II}>0.46$ or Pr $(Q/S_{II}>0)>0.90$. This is in harmony with Smith and Montgomery's advice of avoiding $P/S_{II}<0.4$.

This pursuit says nothing about the probability of P/S_{II}, which are geographically dependent. For example, for a near-impervious parking lot of CN = 99, S = 0.10 in, and almost all storms would be "large" events. On the other hand, on a very porous forested watershed of CN = 40, S = 15 inches, and a storm of 3 inches would be "small". The occurrence of P/S_{II} is largely a matter of geologic and meteorologic happenstance.

Determining CN from Data

Although the CN method is usually used in a prediction mode with CN values estimated by handbook methods from soils and vegetation information, it should also possible to determine CNs from observed event rainfall and runoff data for small watersheds. Equation 1 can be solved for S to yield

$$S = 5\ (P + 2Q - \sqrt{4Q^2 + 5PQ}) \qquad (13)$$

Thus any P and Q pair with Q>0 leads to an S and to a CN via Eq. 2. From the rhetoric in the preceding section, however, low P/S events should be excluded when determing CN from field data. The ideal sample should contain a balanced random scatter of events on both sides of AMC II, which would happen only in high P/S_{II} situations. Low P/S_{II} events would have runoff only above AMC II. Therefore, analysis to determine a S_{II} as a mean (or median) of a series of events, using Eq. 13, should exclude all points for which $P/S_{II}<0.46$. This is awkward, because S_{II} is defined or estimated from the same data body used to determine sample point acceptability. The task is to censor the data set so that all remaining points used to calculate S_{II} (as a mean or median) have $P/S_{II}>0.46$.

This may be accomplished by trial-and-error on a computer. The procedure is briefly described as follows:

1) Use the biggest rainstorm and calculate S from Eq. 13, and CN from Eq. 2.

2) Check for P/S>0.46.

3) If P/S>0.46 then add next biggest storm to the calculation, and use mean S values. Go back to step 2.

4) Include all events down to point where the last P divided by the mean (or median) S is greater than 0.46.

To illustrate this, a number of small watershed data sets are described in Table 4. While Table 5 shows the outcome of the CN determinations. Figure 4 shows a plot and fit by this "P/S" method for the Chickasha, Oklahoma data set.

The exercise leads to some interesting points. First, the "P/S>0.46" data censoring produces lower CNs, as shown in Table 5. This occurs because the high AMC events at low P infer higher CNs, and these are excluded. In a larger data treatment of 90 watersheds (not included here) this was the finding in every case.

Table 4. Watershed and Data Description

Name	Location	Area(AC)	Events	Period	Source of Data
3 Bar D	Ariz.	82	171	1956-79	J.D. Hewlett, ref. 3 (USFS data
Badger Wash 2A	Colo.	107	66	1953-66	USGS, via ref. 2
Dugout Cr.	Wyom.	518	37	1965-72 1982-83	USGS, via ref. 10, and J. Rankl
Ephiriam A.	Utah	11.2	67	1916-29	USFS, via ref 1
Chickasha 5	Okla.	23.7	73	1967-77	USDA, ARS
Zululand 16	S. Africa	796	43	1976-79	ref. 6

Table 5

Data Analysis and Curve Number Determination

	All Events			P/S > .46[1]		
Watershed	$\overline{CN}$	$\overline{P}$(in)	N	$\overline{CN}$	$\overline{P}$(in)	N
3 Bar D	58.5	2.04	171	26.3	14.14	1
Badger 2A	93.8	0.44	66	90.7	0.76	22
Dugout	95.0	0.49	37	93.6	0.65	18
Ephriam A	89.0	0.44	67	undef[2]		0
Chickasha 5	77.6	1.37	73	68.6	2.87	9
Zululand 16	76.1	2.07	43	65.8	4.95	10

Notes: 1. The parameter S here is the mean S in all the events included. It is taken to represent AMC II.

2. No events whith P/S > 0.46. Maxium storm depth in data set is 1.50 inches.

Second, not all events are useful in detemining CN. As an extreme, the Ephiram A data set contained no events for P/S > 0.46, and thus CN could not be defined. This problem is minimized on high runoff sites with heavy rainstorms. At the alternate extreme, low response sites such as forests on deep soils in areas of tranquil rainstorms might require several decades of data to include a high P/S event. As an example, a site with $CN_{II} = 50$ would require a storm of 4.6 inches to achieve P/S = .46. In widespread areas of the western U.S., daily rainfalls of 4.6 inches are at a return period of at least several hundred years. Thus, lower CNs may defy practical identification within our lifetime.

Third, while this "P/S>.46" procedure censors data to minimize calculation bias, it also reduces effective sample size and thus adds uncertainty, which is a function of $N^{-0.5}$. Some practical accomodation of these two problems would be useful, though none is offered here. The use of 0.46 as a rejection level for P/S is based on judgment only and draws from the 90% probablility associated with it.

Last, the criteria of P/S > .46 leads to an alternate expression. By manipulation of Equation 3, it can be easily shown that

$$Q/P = (P/S - .2)^2/((P/S)(P/S + .8)) \qquad (14)$$

Here, when P/S = .46, Q/P = .12. This suggest that Q/P > .12 might be used a convenient rule-of-thumb for quick checks of data sets. At least one point should have Q > .12 P for acceptable (P/S > .46) CN determination. This is a necessary but not sufficient condition.

Acknowledgements

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Literature Cited

1. Forsling, C. L. 1931. A study of the Influence of Herbaceous plant cover on surface run-off and Erosion in relation to Grazing on the Waatch Plateau in Utah. Tech. Bulletin 220, USDA, Washington D. C.

2. Lusby, Gregg C., V. H. Reid, and O. D. Knipe. 1971. Effects of Grazing on the Hydrology and Biology of the Budger Wash Basin in Western Colorado, 1953 - 1966. U. S. Geological Survey Water-Supply Paper 1532D, 90 pp. USGPO, Washington.

3. Hewlett, J. D., J. C. Forsten, and G. B. Cunningham. 1984. Additional tests of the effect of rainfall intensity on storm flow and peak flow from wild-land basins. Water Resources Research 20, 7,985 - 994.

4. Hjelmfelt, A. T. Jr. 1982. Closure on "Empirical Investigation of the Curve Number Technique". Proc. Am. Soc. Civ. Eng. 108(HY4)

5. Hjelmfelt, A. T. Jr. K. A. Kramer, and R. E. Burwell. 1981. Curve Numbers as Random Variables. Proceedings, Internationl Symposium on Rainfall-Runoff Modeling, Mississippi State University. Water Resources Publications. Littleton, Colorado.

6. Hope, A. S. 1982. Estimation of Stormflow Volumes from Small Catchments. Report 1/82, Hydrological Research Unit, University of Zululand. Republic of South Africa. ca 150 pp.

7. Rallison, R. E. 1980. Origin and Evolution of the SCS Runoff Equation. Proceedings Symposium on Watershed Management, Volume II. Amer. Soc. Civ. Eng., New York, pp. 910-924.

8. Rallison, R. E., and R. G. Cronshey. 1979. Discussion of "Runoff Curve Numbers with Varying Site Moisture" Proc. Am. Soc. Civ. Eng. 105(IR4), 439-441.

9. Rallison, R. E., and N. Miller. 1981. Past, Present, and Future SCS Runoff Procedure. Proceedings of International Symposium on Rainfall-Runoff Modeling, Mississippi State University.

10. Rankl, J. G., and D. S. Barker. 1977. Rainfall and Runoff Data from Small Basins in Wyoming. Wyoming Water Planning Program Report No. 17. 195 pp.

11. Smith, R. E., and R. J. Montgomery. 1980. Dicussion on "Runoff Curve Numbers for Partial Area Watersheds". Proc. Am. Soc. Civ. Eng. 106(IR4), 6379-381.

12. Sobhani, G. 1975. A Review of Selected Small Watershed Design Methods for Possible Adoption to Iranian Conditions. MS Thesis, Utah State University. 120 pp

13. Springer, E. P., B. J. McGurk, R. H. Hawkins, and G. B. Coltharp. 1980. Curve Numbers from Watershed Data. Proceedings Symposium on Watershed Management 1980. Am Soc. Civ. Eng., New York, pp 938-950.

14. U.S. Department of Agriculture. 1963 (et seq.). National Engineering Handbook, Section 4, Hydrology. USGPO. Washington.

Figure Titles

Figure 1. The CN method rainfall-runoff relationships, standardized on the storage parameters at AMC II. The upper and lower curves are for AMC III and I, respectively. The figure represents equations 3, 6, and 7.

Figure 2. Experienced variability in CN and handbook AMC I and III criteria from Hjelmfelt, Kramer, and Burwell C).

Figure 3. Probability of $Q/S_{II}>0$ as a function of P/S_{II}. This fits a lognormal distribution closely.

Figure 4. Storm rainfall and runoff for Chickasha Watershed 5, Oklahoma. Only the points as "+" are used in the calculation of CN = 68.6. In this case, the inclusion of the next highest point (P = 2.27 in, Q = 0.06 in) would lead to CN = 67.4, S = 4.84, and P/S = .44, approximately.

Appendix 2. Examples of Job Control Language for the ORSER programs on the IBM 370 computer, and their outputs.

TPINFO program:

```
**** TSO FOREGROUND HARDCOPY ****
DSNAME=SEANH15.AD.OR.TPINFO.CNTL

//SEANHAZ1 JOB (4071090299,RJ029),'ZFVENBERGEN',MSGLEVEL=(1,1),
//   CLASS=B,TIME=(,20),PRTY=3
/*ROUTE  PRINT RMT29
//JOBLIB DD DSN=SEANH02.ATJJ.ORSERLIB,DISP=SHR
//STEP1 EXEC PGM=TPINFO,REGION=200K
//FT06F001 DD SYSOUT=A
//FT09F001 DD SYSOUT=A,DCB=(RECFM=FA,BLKSIZE=133)
//FT08F001 DD UNIT=TAPE9,VOL=SER=W08585,LABEL=(11,SL,,IN),
//   DCB=(RECFM=VBS,LRECL=3696,BLKSIZE=3700),
//   DSN=SEANH02.ATJJ.OR.OK6-74.S4.DATA,DISP=(OLD,KEEP)
//FT05F001 DD *
ID
TABLE
RESPONSE
```

Output:

```
                OFFICE FOR REMOTE SENSING OF EARTH RESOURCES
                     THE PENNSYLVANIA STATE UNIVERSITY

                         T A P E   I N F O R M A T I O N
                         *******************************

                          FILE IDENTIFICATION RECORD
                          --------------------------

              TAPE IDENTIFICATION........................... RS0018   , FILE   1
              FLIGHTLINE OR USER IDENTIFICATION..........
              PLATFORM DESCRIPTION.......................
              SCANNER DESCRIPTION........................
              DATE THIS DATA SET WAS PREPARED............
              USER WHO PREPARED THIS DATA SET............
              SUBSET SOURCE TAPE.........................          , FILE   1
              SCENE/FRAME ID............................. 1706-16332
              DAY NUMBER RELATIVE TO LAUNCH
                  AT TIME OF OBSERVATION................. 706
              HOUR AT TIME OF OBSERVATION................ 16
              MINUTE AT TIME OF OBSERVATION.............. 33
              TENS OF SECONDS AT TIME OF OBSERVATION..... 2

TAPE SEQUENCING NUMBERS............ 4 OF 4               DATA RECORD LENGTH.................   3294
MSS ADJUSTED LINE LENGTH...........   3240               SUN ELEVATION ANGLE................  60 DEG
DATE OF EXPOSURE................... 24 JUN. 74          SUN AZIMUTH........................ 104 DEG
IMAGE FORMAT CENTER                                      SATELLITE HEADING.................. 189 DEG
     LATITUDE...................... N -  34 DEG 40 MIN   REVOLUTION NUMBER.................. 9944
     LONGITUDE..................... W - 098 DEG 31 MIN   TYPE OF ORBIT...................... 0
NADIR POINT                                              ERTS MISSION NUMBER................ 1
     LATITUDE...................... N -  34 DEG 40 MIN   DIRECT OR RECORDED MSS DATA........ 0
     LONGITUDE..................... W - 098 DEG 19 MIN   MSS DATA ACQUISITION SITE.......... G

                       CHANNEL NUMBERS AND SPECTRAL BANDS
                       ----------------------------------
                  CHANNEL NUMBER          SPECTRAL BAND(MICRONS)
                        1                     0.50 -  0.60
                        2                     0.60 -  0.70
                        3                     0.70 -  0.80
                        4                     0.80 -  1.10

                           TABLE OF CONTENTS RECORD
                           ------------------------

BEG. LINE   END LINE   BEG. EL.   END EL.   LINE INC.   EL. INC.   SCAN LINES   ELEMENTS
---------   --------   --------   -------   ---------   --------   ----------   --------
    1         1100       2425      2800         1           1         1100         376

FIRST RECORD IN THIS FILE:        1
```

SUBSET program:

```
**** TSO FOREGROUND HARDCOPY ****
DSNAME=SEANH15.AD.OR.SUBSET.CNTL

//SEANHAZ1 JOB (4071090299,RJ029),'ZEVENBERGEN',MSGLEVEL=(1,1),
//   CLASS=B,TIME=(,20),PRTY=3
/*ROUTE  PRINT RMT29
//JOBLIB DD DSN=SEANH02.ATJJ.ORSERLIB,DISP=SHR
//STEP1 EXEC PGM=SUBSET,REGION=300K
//FT06F001 DD SYSOUT=A
//FT08F001 DD UNIT=TAPE9,VOL=SER=W08585,DISP=(OLD,KEEP),
//   LABEL=(11,SL,,IN),DSN=SEANH02.ATJJ.OR.OK6-74.S4.DATA
//FT09F001 DD UNIT=TAPE9,DISP=(NEW,KEEP,DELETE),
//   DSN=SEANH15.SUBSET.OKLAHOMA.DATA,
//   DCB=(RECFM=VBS,LRECL=3696,BLKSIZE=3700),LABEL=(1,SL)
//FT05F001 DD *
BLOCK     400  500 2501 2600    1    1
CHANNELS 1 2 3 4
END
```

Output:

```
                    OFFICE FOR REMOTE SENSING OF EARTH RESOURCES
                        THE PENNSYLVANIA STATE UNIVERSITY


                              S U B S E T   P R O G R A M
                              ***************************

          SUBSET FROM TAPE:         , FILE 1

          SUBSET ONTO TAPE: RS0018, FILE 1

          CHANNELS ON TAPE:    1  2  3  4

          CHANNELS SUBSET:     1  2  3  4

        INPUT TAPE TABLE OF CONTENTS
       --------------------------------
BEG. LINE   END LINE   BEG.EL.   END EL.    LINE INC.   EL. INC.   SCAN LINES   ELEMENTS

     1        1100       2425      2800         1           1         1100        376

        REQUESTED TABLE OF CONTENTS
       --------------------------------
BEG. LINE   END LINE   BEG.EL.   END EL.    LINE INC.   EL. INC.   SCAN LINES   ELEMENTS

    400        500       2501      2600         1           1           0           0

       OUTPUT TAPE TABLE OF CONTENTS
       --------------------------------
BEG. LINE   END LINE   BEG.EL.   END EL.    LINE INC.   EL. INC.   SCAN LINES   ELEMENTS

    400        500       2501      2600         1           1          101         100
```

NMAP program:

```
**** TSO FOREGROUND HARDCOPY ****
DSNAME=SEANH15.AD.OR.NMAP.CNTL

//SEANHAZ1 JOB (4071090299,RJ029),'ZEVENBERGEN',MSGLEVEL=(1,1),
//   CLASS=B,TIME=(,20),PRTY=3
/*ROUTE  PRINT RMT29
//JOBLIB DD DSN=SEANH02.ATJJ.ORSERLIB,DISP=SHR
//STEP1 EXEC PGM=NMAP,REGION=500K
//FT06F001 DD SYSOUT=A
//FT08F001 DD UNIT=TAPE9,VOL=SER=W06824,
//   DSN=SEANH15.SUBGM.OKLAHOMA.DATA,DISP=(OLD,KEEP),
//   DCB=(RECFM=VBS,LRECL=3696,BLKSIZE=3700),LABEL=(1,SL,,IN)
//FT09F001 DD SYSOUT=A,DCB=(RECFM=FA,BLKSIZE=133)
//FT05F001 DD *
BLOCK      401  450 2501 2600     1     1
CHANNELS    2    4
END
/*
```

Output NMAP program:

```
                         OFFICE FOR REMOTE SENSING OF EARTH RESOURCES
                            THE PENNSYLVANIA STATE UNIVERSITY
                                        AT  0: 0


                          TAPE NAME.......... RS001R
      SCENE/FRAME ID............... 1706-16332     FLIGHTLINE OR USER ID.......
      DATE OF EXPOSURE............ 29 JUN, 74     TAPE SEQUENCING NUMBERS..... 4 OF 4

            B R I G H T N E S S   C L A S S I F I C A T I O N   M A P P I N G
            ================================================================



   CHANNELS USED:  2  4

   NO. OF GRAY SCALE LEVELS FOR EACH CHANNEL:
   CHANNELS:  2      4
             128.   128.

   CLASS LIMITS DETERMINED AUTOMATICALLY.

   CLASS SPECIFICATIONS
   --------------------
     SYMBOL   LIMIT
     ------   -----
       X      21.33
       +      22.58
       -      23.81
             100.00


   PROGRAM: NMAP
   DATE AND TIME:              0: 0
   TAPE NAME: RS001R
   BLOCK SPECIFICATIONS:   401  450 2501 2600     1     1

            SYMBOL COUNT
            ------------
   SYMBOL  LIMIT      COUNT  PER CENT
   ------  -----      -----  --------
     X     21.33      1205.     24.
     +     22.58      1320.     26.
     -     23.81      1303.     26.
          100.00      1172.     23.

   AVERAGE RESPONSE PER ELEMENT FOR EACH CHANNEL:
   CHANNELS:  2      4
             33.0   23.7

   MAXIMUM RESPONSE IN THE BLOCK FOR EACH CHANNEL:
   CHANNELS:  2      4
              50.    32.

   MINIMUM RESPONSE IN THE BLOCK FOR EACH CHANNEL:
   CHANNELS:  2      4
              18.    12.

   AVERAGE NORM PER ELEMENT:     40.7
   MAXIMUM NORM IN THE BLOCK:     58.
   MINIMUM NORM IN THE BLOCK:     30.
```

PROGRAM: NMAP
DATE AND TIME: 0: 0
TAPE NAME: RS001B

BLOCK SPECIFICATIONS

BEGINNING LINE	401
ENDING LINE	450
BEGINNING ELEMENT	2501
ENDING ELEMENT	2600
LINE INCREMENT	1
ELEMENT INCREMENT	1

Appendix 3. Examples of SAS programs used in the Landsat analysis.

```
**** TSO FOREGROUND HARDCOPY ****
DSNAME=SEANH15.AO.SAS.AVREFL.CNTL

//SEANHAZ1 JOB (4071090299,RJ029),'ZEVENBERGEN',CLASS=C,
//  TIME=(0,20),PRTY=13
/*ROUTE PRINT RMT29
// EXEC SAS
//OKLAHOMA DD UNIT=SYSDA,DSN=SEANH03.AD.DIGIT3.DATA,DISP=SHR
//SYSIN DD *
DATA OKLA;
  INFILE OKLAHOMA;
  INPUT DATE 1-3 WTRSHED $ 5-6 PIXNUM 8-9 DIG4 11-12 DIG5 14-15
        DIG6 17-18 DIG7 20-21;
  IF DATE= 96 THEN SIN=0.78;
  IF DATE=240 THEN SIN=0.81;
  IF OATE=348 THEN SIN=0.44;
  IF DATE=181 THEN SIN=0.87;
  IF OATE=289 THEN SIN=0.63;
  REFL4=(DIG4/289)/SIN;
  REFL5=(DIG5/306)/SIN;
  REFL6=(DIG6/284)/SIN;
  REFL7=(DIG7/125)/SIN;
  OUTPUT;
PROC SORT OATA=OKLA;
  BY WTRSHED DATE;
PROC MEANS NOPRINT;
  BY WTRSHEO DATE;
  VAR REFL4 REFL5 REFL6 REFL7;
    OUTPUT OUT=REFMEAN MEAN=RMEAN4 RMEAN5
           RMEAN6 RMEAN7 STO=SD4 SD5 SD6 SO7;
PROC PRINT;
    TITLE REFLECTIONS BY WATERSHED ANO OATE;
PROC PLOT UNIFORM;
  PLOT RMEAN4*DATE='*' RMEAN5*DATE='*' RMEAN6*DATE='*'
       RMEAN7*DATE='*'/HZERO VAXIS=0.10 TO 0.28 BY 0.01 HPOS=80;
```

Calculation of the average reflection in four bands on five different dates for Landsat-1 data.

```
**** TSO FOREGROUND HARDCOPY ****
DSNAME=SEANH15.AD.SAS.REFCHAR.LNDST2.CNTL

//SEANHAZ1 JOB (4071090299,RJ029),'ZEVENBERGEN',CLASS=C,
//  TIME=(0,20),PPTY=3
/*ROUTE PRINT RMT29
// EXEC SAS
//DIG OO UNIT=SYSDA,DSN=SEANH15.DIG.WFDC1.OATA,DISP=SHR
//SYSIN DD *
DATA DIG;
  INFILE DIG;
  INPUT LINE EL DIG4 DIG5 DIG6 DIG7;
  SIN=0.848;
  REFL4=0.1775*((DIG4/63.5)+0.10)/SIN;
  REFL5=0.2074*((DIG5/85.81)+0.07)/SIN;
  REFL6=0.2540*((DIG6/95.49)+0.07)/SIN;
  REFL7=0.1261*((DIG7/15.71)+0.14)/SIN;
  DROP LINE EL SIN;
PROC MEANS;
  VAR REFL4 REFL5 REFL6 REFL7;
  TITLE MEANS AND VARIANCES OF REFLECTION;
PROC CORR OATA=DIG OUT=CORREL;
  VAR REFL4 REFL5 REFL6 REFL7;
  TITLE CORRELATIONS AND MEANS OF THE FOUR BANDS;
PROC CHART DATA=DIG;
  HBAR REFL4 REFL5 REFL6 REFL7;
  TITLE REFLECTION DISTRIBUTION IN FOUR BANDS;
```

Program prints horizontal histograms for the distribution of reflection values in four bands, for Landsat-2 data.

Calculation of reflectance index models for five different dates, and correlation coefficients of these values and ground truth.

```
**** TSO FOREGROUND HARDCOPY ****
DSNAME=SEANH15.AD.SAS.VIREFL.CORR.CNTL

//SEANHAZ1 JOB (4071090299,RJ029),'ZEVENBERGEN',CLASS=C,
//  TIME=(0,20),PRTY=13
/*ROUTE PRINT RMT29
// EXEC SAS
//OKLAHOMA DD UNIT=SYSDA,DSN=SEANH03.AD.OKDIGIT2.DATA,DISP=SHR
//GROUND DD UNIT=SYSDA,DSN=SEANH03.AD.OK.GROUND.DATA,DISP=SHR
//SYSIN DD *
DATA OKLA;
  INFILE OKLAHOMA;
  INPUT DATE 1-2 WTRSHED $ 4-5 PIXNUM 7-8 DIG4 10-11 DIG5 13-14
        DIG6 16-17 DIG7 19-20;
  IF DATE=04 THEN SIN=0.78;
  IF DATE=08 THEN SIN=0.81;
  IF DATE=12 THEN SIN=0.44;
  IF DATE=06 THEN SIN=0.87;
  IF DATE=10 THEN DELETE;
  A1=(DIG4/289)/SIN;
  A2=(DIG5/306)/SIN;
  A3=(DIG6/284)/SIN;
  A4=(DIG7/125)/SIN;
  ND6=(A3-A2)/(A3+A2);
  ND7=(A4-A2)/(A4+A2);
  TVI6=SQRT(ND6+.5);
  TVI7=SQRT(ND7+.5);
  SBI=0.332*A1+0.603*A2+0.675*A3+0.262*A4;
  GVI=-0.283*A1-0.660*A2+0.577*A3+0.388*A4;
  YVI=-0.899*A1+0.482*A2+0.076*A3-0.041*A4;
  NSI=-0.016*A1+0.131*A2-0.452*A3-0.882*A4;
  PVI6=SQRT((-2.507-0.457*A1+0.498*A3)**2+(2.734+0.498*A2-0.543*A3)**2);
  PVI7=SQRT((.355*A4-.149*A2)**2+(.355*A2-.852*A4)**2);
  DVI=2.4*A4-A2;
  AVI=2*A4-A2;
  R54=A2/A1;
  R65=A3/A2;
  R75=A4/A2;
  DROP DIG4 DIG5 DIG6 DIG7 PIXNUM SIN;
PROC SORT;
  BY WTRSHED DATE;
PROC MEANS NOPRINT;
  BY WTRSHED DATE;
  VAR ND6 ND7 TVI6 TVI7 SBI GVI YVI NSI PVI6 PVI7 DVI AVI R54
      R65 R75 A1 A2 A3 A4;
  OUTPUT OUT=VIMEAN MEAN=AVND6 AVND7 AVTVI6 AVTVI7 AVSBI AVGVI
                         AVYVI AVNSI AVPVI6 AVPVI7 AVDVI AVAVI
                         AVR54 AVR65 AVR75 AVA1 AVA2 AVA3 AVA4;
DATA GROUND;
  INFILE GROUND;
  INPUT RAIN 1-4 PERCVEG 6-7 FRBIO 9-13 DRBIO 15-19;
DATA CORREL;
  MERGE VIMEAN GROUND;
PROC PRINT;
  TITLE NEW DATA SET CONTAINING AVERAGE VEGETATION INDICES;
  TITLE2 AND GROUND TRUTH BY WATERSHED AND DATE;
PROC CORR BEST=5;
  VAR RAIN PERCVEG FRBIO DRBIO;
  WITH AVND6 AVND7 AVTVI6 AVTVI7 AVSBI AVGVI AVYVI AVNSI AVPVI6
       AVPVI7 AVDVI AVAVI AVR54 AVR65 AVR75 AVA1 AVA2 AVA3 AVA4;
```

Appendix 4. Summary of Curve Number Computations

WATERSHED		State or Country	Area (Acres)	Events	Mean Nat	Mean Ord	Regression Nat	Regression Ord	Large Storms Nat	Large Storms ord
Alladin	3	WY	11.6	10	83	84	75	79	**	77
Alpine MDW		UT	376	10	86	87	81	81	**	**
Badger Wsh	1A	CO	42	54	94	95	92	93	92	94
Badger Wsh	1B	CO	54	37	93	93	91	92	91	93
Badger Wsh	2A	CO	107	66	94	94	92	92	91	93
Badger Wsh	2B	CO	101	55	92	93	90	91	88	91
Badger Wsh	3A	CO	38	66	95	95	94	94	93	95
Badger Wsh	3B	CO	31	62	94	94	93	93	93	94
Badger Wsh	4A	CO	14	58	94	95	94	94	92	94
Badger Wsh	4B	CO	12	51	93	93	91	92	89	92
Badwater		WY	3750	20	90	90	85	86	**	**
Bar-D	3	AZ	82	171	59	58	26	27	25	25
Beaver	2	AZ	126	14	75	75	60	64	63	65
Beaver	3	AZ	362	16	75	76	67	69	64	68
Beaver	4	AZ	346	20	73	73	68	68	71	71
Beaver	5	AZ	66	25	73	73	66	68	63	67
Beaver	16	AZ	252	9	72	72	70	70	68	68
Beaver	17	AZ	299	22	79	80	82	83	75	76
Berea	6	KY	287	84	84	84	87	88	83	84
Boco Mtn	1	CO	7.4	52	90	90	84	87	**	86
Bow Trib		WY	1926	22	91	91	84	85	86	86
Chichasha	7	OK	19.19	171	86	87	82	85	82	86
Chickasha	5	OK	23.72	73	78	78	71	74	69	75
Chickasha	6	OK	27.22	105	76	76	71	74	67	73
Chickasha	8	OK	27.55	183	82	83	78	80	76	80
Coal Cr	TRB	UT	262	5	88	89	85	85	**	**
Cottonwood	4	SD	8.6	28	80	81	71	74	69	72
Deadhorse	1	WY	979	18	95	96	96	96	95	96
Deadhorse	2	WY	857	21	95	96	92	92	94	94
Deep Creek	3	TX	2189	25	65	65	57	60	54	60
Deep Creek	8	TX	2765	22	71	71	69	72	65	72
Drychy	WFD	WY	1184	15	91	91	88	87	87	87
Dugout	LNG	WY	518	37	95	95	92	92	94	95

Appendix 4 cont.

Ephriam	A	UT	11.24	67	89	89	80	85	**	86
Ephriam	B	UT	8.97	38	85	85	59	74	**	**
Escondido		TX	2105	9	63	62	44	45	45	45
Eteapot		WY	3842	17	89	89	84	85	82	84
Frank Draw		WY	506	12	89	87	87	87	87	87
Gillies	DRW	WY	832	14	94	94	88	90	86	86
Green Cr	1	TX	2138	19	70	70	66	68	65	65
Halfway		UT	484	14	75	75	64	64	**	**
Hastings	1	NE	3.62	25	62	62	50	53	**	51
Hastings	3	NE	4.26	41	78	78	78	79	77	78
Hastings	7	NE	3.62	41	79	80	77	79	77	79
Hastings	1H	NE	3.77	37	61	60	52	54	51	51
Headgate	DRW	WY	2125	12	89	89	84	84	84	84
Honey Cr	12	TX	806	22	81	81	82	83	81	82
Kendall	2	AZ	4.6	14	86	86	81	84	84	85
Luckyhills	1	AZ	2.8	47	87	87	87	88	85	87
Luckyhills	2	AZ	3.9	50	87	87	87	87	85	86
Luckyhills	3	AZ	8.3	41	87	87	86	86	84	86
Luckyhills	4	AZ	11	38	87	87	86	86	85	86
Luckyhills	5	AZ	.56	58	88	88	88	89	86	87
Luckyhills	6	AZ	0.85	48	87	88	88	89	86	87
McKenzie	DRW	WY	1293	13	88	88	77	77	75	75
Monument	DRW	WY	5267	17	89	89	84	85	82	84
Morris		UT	156	17	74	74	61	62	**	**
Mudspring		WY	5651	20	91	91	67	67	**	**
Mukewater		TX	2573	11	71	71	57	58	64	64
Murphy	DRW	WY	1585	23	93	93	88	89	88	89
Newell	12	SD	89.9	28	89	90	89	90	87	91
Nowater		WY	2412	19	92	92	86	86	86	86
Nowater	2	WY	1350	16	90	90	83	83	82	82
Nowood		WY	966	15	93	93	89	91	87	90
Prichard	DRW	WY	3264	25	92	93	88	89	86	90
Reynlds Mt	EST	ID	100	43	81	81	59	59	**	**
Reynolds	3	ID	306	12	77	78	70	71	**	**
Riesel	1	TX	174	38	83	84	82	83	83	84
Riesel	2	TX	130	36	80	81	81	82	80	81

Appendix 4 Cont.

Riesel	D	TX	1110	32	83	84	83	84	83	84
Sage		WY	883	12	82	82	76	78	**	82
Seven Spgs	WST	AZ	482	20	83	83	69	75	**	**
Seven Spgs	EST	AZ	748	26	84	84	71	73	**	**
Soldier Cr	TRB	UT	800	6	94	94	92	92	90	90
Sonora	1	TX	10.2	13	73	73	80	81	76	74
Sonora	2	TX	8.6	10	80	80	88	88	84	85
Sonora	3	TX	6.7	10	67	67	69	69	72	71
Sonora	4	TX	7.2	8	58	57	46	46	47	47
Sonora	5	TX	4.5	10	71	71	72	72	74	74
Sonora	6	TX	6.9	7	65	65	61	62	64	66
Thirdsand		WY	6912	21	90	91	83	84	84	84
Thomas Cr	NOR	AZ	441	9	65	65	47	48	**	**
Thomas Cr	SOU	AZ	601	12	68	68	53	54	**	**
Tombstone	W4	AZ	560	17	80	81	76	79	**	79
Wattis Cr	TRB	UT	3130	6	93	93	87	87	**	**
WFDC	DC	WY	442	17	92	92	89	90	89	89
Willow Spr	DRW	WY	1267	20	90	90	74	74	73	73
Zululand	15	SA	3373	43	77	77	71	72	71	72
Zululand	16	SA	796	43	76	76	65	65	66	67
Zululand	17	SA	91.4	43	77	77	67	67	70	71

Appendix 5. Examples of some SAS and FORTRAN programs used in the curve number analysis.

Calculation of the mean curve number, and by non-linear regression for natural data.

```
**** TSO FOREGROUND HARDCOPY ****
DSNAME=SEANH15.AD.SAS.LSQCN.CNTL

//SEANHAZ1 JOB (4071090299,RJ029),'ZEVENBERGEN',CLASS=C,
//  TIME=(0,20),PRTY=13
/*ROUTE PRINT RMT29
// EXEC SAS
//IN DD UNIT=SYSDA,DSN=SEANH15.R5.DATA,DISP=SHR
//STAT DD UNIT=SYSDA,DSN=SEANH15.STATCN.R5.DATA,DISP=(NEW,CATLG),
//  SPACE=(TRK,(20,5),RLSE),DCB=(LRECL=80,BLKSIZE=4560,RECFM=FB)
//SYSIN DD *
DATA IN;
  INFILE IN;
  INPUT P Q;
    S=5*(P+(2*Q)-((4*(Q**2))+(5*P*Q))**0.5);
    RCN=1000/(10+S);
    DROP S;
PROC PRINT;
PROC MEANS N MEAN STD SUM;
     OUTPUT OUT=STATS
     N=NUM MEAN=MEANP MEANQ MEANCN STD=STDP STDQ STDCN
     SUM=SUMP SUMQ SUMCN;
DATA STAT;
     SET STATS;
     FILE STAT;
     PUT NUM MEANP MEANQ MEANCN STDP STDQ STDCN SUMP SUMQ SUMCN;
PROC NLIN DATA=IN;
    PARMS CN=50 TO 100 BY 5;
    P0=200/CN-2;
    IF P<=P0 THEN DO;
    MODEL Q=0;
    DER.CN=0;
    END;
    ELSE DO;
    MODEL Q=(P-200/CN+2)*(P-200/CN+2)/(P+800/CN-8);
    DER.CN=(400*(P-200/CN+2)*(P+800/CN-8)/(CN*CN)-
           (P-200/CN+2)*(P-200/CN+2)*(-800/(CN*CN)))/
           ((P+800/CN-8)*(P+800/CN-8));
    END;
    OUTPUT OUT=NEW PREDICTED=QP RESIDUAL=RP;
PROC PRINT;
PROC PLOT;
    PLOT Q*P QP*P='*' / OVERLAY HPOS=80 VPOS=40;
```

Calculation of the mean curve number, and by non-linear regression for ordered data.

```
**** TSO FOREGROUND HARDCOPY ****
DSNAME=SEANH15.AD.SAS.LSQORD.CNTL

//SEANHAZ1 JOB (4071090299,PJ029),'ZEVENBERGEN',CLASS=C,
//  TIME=(0,20),PRTY=13
/*ROUTE PRINT RMT29
// EXEC SAS
//IN DD UNIT=SYSDA,DSN=SEANH15.R5.DATA,DISP=SHR
//STAT DD UNIT=SYSDA,DSN=SEANH15.MEANORD.R5.DATA,DISP=(NEW,CATLG),
//  SPACE=(TRK,(20,5),RLSE),DCB=(LRECL=80,BLKSIZE=4560,RECFM=FB)
//NEW DD UNIT=SYSDA,DSN=SEANH15.LSCNORD.R5.DATA,DISP=(NEW,CATLG),
//  SPACE=(TRK,(20,5),RLSE),DCB=(LRECL=80,BLKSIZE=4560,RECFM=FB)
//SYSIN DD *
DATA IN;
  INFILE IN;
  INPUT P Q;
PROC SORT;
   BY P;
DATA AAP;
   SET IN;
   DROP P;
PROC SORT;
   BY Q;
DATA NOOT;
   SET IN;
   DROP Q;
DATA MIES;
   MERGE NOOT AAP;
     S=5*(P+(2*Q)-((4*(Q**2))+(5*P*Q))**0.5);
     RCN=1000/(10+S);
     DROP S;
PROC PRINT;
PROC MEANS N MEAN STD SUM;
      OUTPUT OUT=STATS
      N=NUM MEAN=MEANP MEANQ MEANCN STD=STDP STDQ STDCN
      SUM=SUMP SUMQ SUMCN;
DATA STAT;
      SET STATS;
      FILE STAT;
      PUT NUM MEANP MEANQ MEANCN STDP STDQ STDCN SUMP SUMQ SUMCN;
PROC NLIN DATA=MIES;
     PARMS CN=20 TO 100 BY 5;
     P0=200/CN-2;
     IF P<=P0 THEN DO;
     MODEL Q=0;
     DER.CN=0;
     END;
     ELSE DO;
     MODEL Q=(P-200/CN+2)*(P-200/CN+2)/(P+800/CN-8);
     DER.CN=(400*(P-200/CN+2)*(P+800/CN-8)/(CN*CN)-
            (P-200/CN+2)*(P-200/CN+2)*(-800/(CN*CN)))/
            ((P+800/CN-8)*(P+800/CN-8));
     END;
     OUTPUT OUT=OLD PREDICTED=QP RESIDUAL=RP PARMS=LSCN;
DATA NEW;
     SET OLD;
     FILE NEW;
     PUT P Q LSCN;
PROC PRINT;
PROC PLOT;
     PLOT Q*P QP*P='*' / OVERLAY HPOS=80 VPOS=40;
```

Calculation of curve numbers using only the events that meet the selection criterion: $P/S_{II}>0.46$.

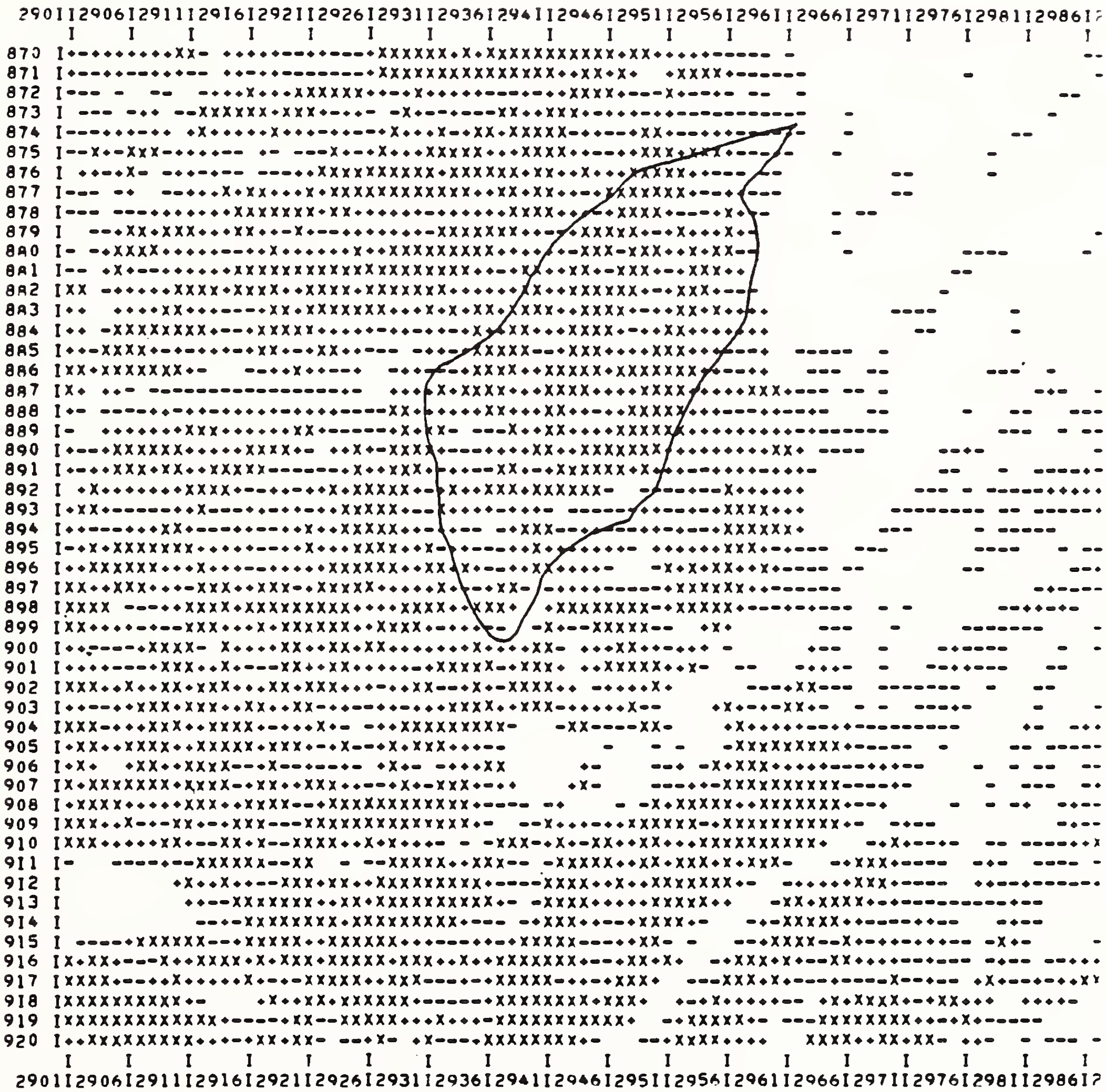
```
**** TSO FOREGROUND HARDCOPY ****
DSNAME=SEANH15.AD.CN.CNTL

//SEANHAZ1 JOB (4071090299,RJ029),'ZEVENBERGEN',CLASS=C,
//     TIME=(0,20),PRTY=13
/*ROUTE PRINT RMT29
//STEP1 EXEC FORTGCLG
//FORT.SYSIN DD *
      DIMENSION P(37),Q(37),CN(37),S(37),FACT(37)
      INTEGER N
      READ (8,10) (P(I),Q(I),I=1,37)
   10 FORMAT (F4.2,F5.2)
      J=37
      WRITE (6,15)
   15 FORMAT (1H1,///,20X,'P(I)',10X,'Q(I)',10X,'S(I)',10X,
     1'CN(I)',//)
      DO 100 I=1,J
      S(I)=5.*(P(I)+2.*Q(I)-(4.*Q(I)*Q(I)+5.*P(I)*Q(I))**0.5)
      CN(I)=1000./(S(I)+10.)
      WRITE (6,20) (P(I),Q(I),S(I),CN(I))
   20 FORMAT (20X,F4.2,10X,F4.2,09X,F5.2,10X,F5.2)
  100 CONTINUE
  150 CONTINUE
      STOT=0.
      DO 200 I=1,J
      STOT=STOT+S(I)
  200 CONTINUE
      SMEAN=STOT/J
      DO 400 I=1,J
      FACT(I)=P(I)/SMEAN
      IF (FACT(I).LT.0.46) GO TO 300
  400 CONTINUE
      GO TO 500
  300 J=J-1
      GO TO 150
  500 CONTINUE
      WRITE (6,15)
      WRITE (6,20) (P(I),Q(I),S(I),CN(I),I=1,J)
      CNSUM=0.
      DO 600 I=1,J
      CNSUM=CN(I)+CNSUM
  600 CONTINUE
      CNMEAN=CNSUM/J
      WRITE (6,30) CNMEAN
   30 FORMAT (//////,20X,'THE AVERAGE CN IS   ',F5.2)
      STOP
      END
//GO.FT08F001 DD UNIT=SYSDA,DSN=SEANH15.AD.DUGOUT.DATA,DISP=SHR
```

Appendix 6. Location of Tombstone W4 on line printer map.

```
PROGRAM: NMAP
DATE AND TIME:          0: 0
TAPE NAME: RS001B

BLOCK SPECIFICATIONS
--------------------
   BEGINNING LINE   870
      ENDING LINE   920
BEGINNING ELEMENT  2901
   ENDING ELEMENT  3000
   LINE INCREMENT     1
ELEMENT INCREMENT     1
```



Appendix 7. Parameters of linear and exponential relationships between curve numbers and reflectance index models for 9 watersheds.

RIM	linear			exponential		
	a1	b1	r	a2	b2	r
CH5	43.82	246.13	0.967	3.894	3.267	0.976
R65	115.45	-23.89	-0.927	4.849	-0.320	-0.944
ND6	96.08	-89.24	-0.950	4.588	-1.189	-0.962
TVI6	206.54	-153.84	-0.955	6.057	-2.046	-0.965
SBI	15.28	191.48	0.938	3.511	2.552	0.950

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